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MATERIAL EVALUATION OF OPTICAL FIBERS AND PAYOUT BOBBINS

AN OVERVIEW

D. J. Adams
M. R. Cates
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Applied Technology Division

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ABSTRACT

This project was undertaken by the Applied Technology Division of the Oak Ridge National Laboratory (ORNL) to provide a cursory assessment of the U.S. Army Missile Command's (MICOM's) Fiber Optic Guided Missile program. MICOM provided funding to ORNL in the amount of $35,000 over the four-month performance period of September through December 1989. The funding was applied to provide staff who could relate its experiences and "lessons learned" to MICOM's program. This report documents the findings and recommendations of that ORNL team.

INTRODUCTION

This project was undertaken by the Applied Technology Division (ATD), Oak Ridge National Laboratory (ORNL), to provide a cursory assessment of the U.S. Army Missile Command's (MICOM's) Fiber Optic Guided Missile program. MICOM provided funding to ORNL in the amount of $35,000 over the four-month performance period of September through December 1989. This funding was applied to provide staff who could relate its experiences and "lessons learned" to MICOM's program.

The team from ORNL for this project consisted of scientists and engineers from ATD. Our experience base included a wide range of pure and application-specific research and development, including backgrounds in nuclear physics and engineering, laser science, fiber-optics technology, analog and digital data acquisition and analysis, fiber composite materials fabrication and testing, mechanical systems engineering, technical software development, full-scale field testing, and systems analysis.

This project consisted of a survey of the technology associated with long-range fiber optic guided missiles, with particular emphasis on recommendations from our technical perspectives. The scale of the project was limited; therefore, we felt the maximum benefit would arise from examining technology with our experience base as a reference. We had little or no information available to us from the technical history of this project, and, therefore, we were not prejudiced by previous research. Also, we were unaware of the level of effort in numerous areas; consequently, we may not have been aware of previously implemented solutions to problems and may have neglected to give them proper credit. This was totally unintentional on our part.

Our approach has been to familiarize ourselves with the Fiber Optic Guided Missile (FOG-M) program through a visit of a few hours and then attempt to relate our experiences to the program. Our sponsors advised us to be as objective as possible and provided us with little information on approaches tried—proved or disproved—which might influence our thinking. This was an interesting approach for evaluating the project, and although we are working from a disadvantageous position regarding knowledge of the program, we believe our analysis will be useful to the program.

No classified information was provided to us; therefore, we excluded classified information from this report. In future work, we would expect to discuss such information as radiation levels in fiber optics, their effect, and shielding techniques. Additionally, we were not briefed on the contractors' production processes and cannot address any differences between MICOM's experimental facilities and those of the actual production process.

A visit was made to MICOM's Research, Development, and Engineering Center on September 15, 1989, which provided an opportunity for ORNL staff members to become familiar with the Fiber Optic Guided Missile program and technology. The following facilities were toured:

- Fiber Payout Facility,
- Fiber Optics Winding Facility,
- Adhesive Accelerated Aging Analysis and Test Facility, and
- Dynamic Tensile Strength Tester Facility.

We have gained an introduction to MICOM's Research, Development, and Engineering Center facilities and staff with this initial funding, and we accomplished a basic understanding of the FOG-M program and technology. Our observations and recommendations will be described in the following sections of this report.

OPTICAL FIBER MATERIALS, COATINGS, AND BUFFERS

The current technological trend among optical fiber manufacturers is the preference for a dual protective coating that encapsulates the central core and the cladding material. The principal functions of the dual polymer coating are to protect the core from low microbending susceptibility and to preserve the inherent strength of the glass fiber. No single coating can provide all the necessary characteristics needed for optical fibers in terms of protection and handleability.[1,2]

These coatings have historically been composed of thermally cured, hot melt or ultraviolet (UV)-curable polymeric formulations and consist of a "soft" inner primary coating and a "hard" outer secondary coating. Presently, the bulk of the development work occurring in the optical fiber industry and published in the literature has been focused on UV-curable systems. These systems offer several desirable feature, including formulation flexibility, diverse properties and fast cure response. The development of newer and better UV-curable systems is expected to continue because the rate-limiting step in the manufacture of optical fibers is the application and cure speeds of the polymer coatings.[1,2]

CORE AND CLADDING MATERIALS

Doped silica (i.e., GeO_2, P_2O_5, or B_2O_3) or pure silica cores are usually the materials of choice for optical fiber manufacturers because of their low intrinsic absorption and scattering losses as well as their ease of fabrication. The cladding materials are generally composed of fluorine-doped silica or pure silica and must always have a lower refractive index relative to the core to insure total internal reflection of the light energy.[2,3]

PRIMARY COATINGS

One of the problems that plagued the optical fiber manufacturers in the past is microbending transmission loss. The chief causative factors contributing to microbending are rough coatings, eccentricity and defects in the coating (i.e., lumps voids, and bending), thermal contraction of the coating and other materials adhered to the coated fiber, and external stresses that can deflect the fiber axis.[2,4]

Minimization of microbending loss can be achieved by using soft primary coatings that buffer or cushion the fiber from stresses that otherwise might result in very high losses of up to tens of decibels per kilometer. There appears to be a strong correlation of microbending sensitivity to the modulus of the primary coating material. This is especially evident at low temperatures when the moduli of the coatings increase. Typically, coatings that have a 30-min tensile relaxation modulus below 1450 psi at the low end of the temperature extreme offer the lowest microbending susceptibilities.[2,4]

Primary coatings typically exhibit low T_g's, high elasticities, and low modulus characteristics (i.e., 100 to 900 psi at room temperature) down to -40°C, are thermally and hydrolytically stable, possess excellent adhesion to glass, and do not evolve hydrogen. The modulus of these coatings is generally controlled by using reactive chain-extending difunctional monomers or oligomers rather than nonreactive, nonfunctional plasticizers. Plasticizers tend to migrate over time from the primary coating into the secondary coating, causing the modulus to decrease in the secondary buffer and increase in the primary buffer. Typical properties of primary coatings composed of UV-cured acrylates for optical fibers are shown below.[2,4,5]

Viscosity at 25° = 5000 cps
Specific gravity at 25°C = 1.14
Tensile strength = 500 psi
Elongation at break = 200%
Tensile modulus at 2.5% = 400 psi
Rupture strength = 800 in.-lb/in.^{3}
Shore A_2 hardness = 50
Refractive index = 1.52
Water perm (U.S. Perms - see ASTM E96) = 15
T_g = -30°C
T_g range = -55 to -10°C
Coefficient of thermal expansion (cm/cm/°C × 10^{-5})
  Below T_g = 8
  Above T_g = 24

UV-curable systems that are currently being used as primary coatings include urethane acrylates, epoxy acrylates, butadiene acrylates, silicones (thermally and UV cured), polyene thiols, acrylates and hot-melt elastomers (i.e., ethylene vinyl acetate and thermoplastic rubbers). Glass fibers are coated with a low-viscosity primary buffer immediately after they are drawn because of their extreme sensitivity to abrasion damage, microflaw formation, hydrolysis, and stress corrosion that significantly degrades the fiber strength. The most widely used primary coatings are composed of urethane acrylates that can be applied and cured at high draw rates. Each UV-curable system has its own inherent limitations including:

1. low curing speeds for most thermally cured silicones and poorer adhesion to glass fibers compared with UV-curable systems

2. butadiene acrylates and hot melts possess poor thermal stability

3. urethane and epoxy acrylates typically have high T_g's and high moduli.[2,4,5,6]

The viscosity of the primary coating is an important factor that is controlled by adjusting the temperature of the coating reservoir during the application process. Small changes in the temperature result in significant decreases in the viscosity of the coating. Low viscosities (i.e., 500 to 6000 cps) allow for easy filtration before coating and ensure coating concentricity and uniformity. The viscosity of the liquid must be increased if beading of the coating becomes a problem.[2,5]

Other important properties that should be taken into consideration when choosing a primary coating are its refractive index, adhesion characteristics, purity and the effect of temperature on the physical properties of the coating. The refractive index should be higher than that of the cladding material to ensure effective cladding mode stripping (i.e., >1.46 for silica). Increased adhesion between the fiber and primary coating has been reported to prevent moisture buildup at the interface, thereby improving the strength and fatigue characteristics of the optical fiber. This improvement may be realized to even a greater extent with coatings having low water absorption values. The primary coating should also be void of any particle contamination because of the increased likelihood of fiber surface damage during drawing and handling. In addition, there should be only a minimal change in the physical properties of the coating over the expected service temperature range.[1,2,4,6]

SECONDARY COATINGS

Secondary coatings are composed of UV-curable and extrusion-coatable materials, including urethane acrylates, epoxy acrylates, polyamides, polyesters, fluoropolymers and liquid crystal polyesters. These coatings are notably high in toughness, abrasion resistance, modulus and T_g relative to the primary coatings. The characteristics cited above contribute an increased level of protection and handleability to the optical fiber that primary buffers cannot provide. Secondary coatings are also required to be thermally and hydrolytically stable and should undergo no hydrogen evolution.[2,4,5]

The most commonly used high-modulus secondary coatings are the UV-curable urethane acrylates or epoxy acrylates. The modulus of these materials can be increased over those of the primary coatings by modifying their molecular structure and/or by increasing their cross-link density. Typical properties of UV-cured acrylates used as secondary coatings are shown below.[4,5]

Viscosity at 25°C = 9000 cps
Specific gravity at 25°C = 1.20
Tensile strength = 2800 psi
Elongation at break = 25%
Tensile modulus at 2.5% = 55,000 psi
Rupture strength = 1000 in.lb/in.^{3}
Shore D = 50
Refractive index = 1.53
Water perm (U.S. Perms - See ASTM E96) = 7

$T_g = -5°C$
$T_g = -50$ to $30°C$
Coefficient of thermal expansion (cm/cm/°C × 10^{-5})
Below $T_g = 9$
Above $T_g = 18$

ULTRAVIOLET-CURABLE COATINGS

Early optical fiber coatings were composed of silicone oils, cellulosic lacquers, blocked urethanes, silicone rubbers and hot melt elastomers. Most of these materials had slow application speeds and changed as a result of environmental aging. Specifically, these materials became brittle after long-term aging at elevated temperatures resulting in microbending loss. In addition, these materials exhibited poor hydrolytic stability under hot, wet conditions which contributed to loss in fiber strength.[5]

Optical fiber coatings have improved significantly over the years in terms of handleability, stability, durability, cure speeds, and application speeds, especially with the development and optimization of UV-curable systems. These systems can be formulated to meet a wide variety of different physical and mechanical properties, and the majority of these systems are based on acrylic functional compositions. They generally cure via a free radical initiated addition reaction and contain acrylic oligomers, reactive monomeric diluents, photoinitiators, and special additives.[5]

Oligomers

Acrylic oligomers used in UV-curable coatings are typically polyesters, polyethers, and epoxy polymers which have undergone esterification with acrylic acid or have been reacted with a diisocyanate and a hydroxy functional acrylate. Generally, these oligomers are in solid form or are so high in viscosity that they must be reacted with reactive with reactive diluents until an optimal application viscosity is obtained. The properties of UV-curable coatings including hardness, flexibility, solvent resistance, durability and adhesion are primarily determined by the composition of the oligomer.[5,7]

Monomers

Reactive monomeric diluents are preferred over nonreactive diluents (i.e., plasticizers) because of the latter's tendency to migrate over time into secondary coatings or to free-energy surfaces. Diluents are generally low molecular weight acrylate esters that act as cross-linking agents and are used as viscosity reducers. These compounds can be categorized in terms of their respective cure speeds:

acrylic > methacrylic > vinyl > allylic[5,8]

It has been proven that there exists a correlation between the T_g of acrylic polymers and their tensile strength and percent elongation. This correlation is illustrated in Table 1.[9]

Table 1. Correlation between the T_g of acrylic polymers and their tensile strength and percent elongation

Compound	Tensile Strength (psi)	Elongation (%)	T_g (°C)
Polymethacrylate			
Methyl	9000	4	105
Ethyl	5000	7	65
Isobutyl	3500	5	48
n-butyl	1000	250	20
Polyacrylate			
Methyl	1000	750	9
Ethyl	33	1800	-22
n-butyl	3	2000	-54

It has also been verified that acrylic polymers containing long alkyl side chains are more resistant to water and alcohol because of the large differences in their solubility parameters. At the other extreme, long alkyl side chain polymers are less resistant to aliphatic solvents because of the close similarity in terms of their solubility parameters.[9]

Hydrolysis of acrylic polymers generally occurs at the ester, ether, or amide side chain linkages leaving the main polymer chain intact, thereby preserving the integrity of the film. Significant differences in the durability of acrylic polymers exist. It has been determined that methacrylates are more durable than the acrylates. In addition, the longer the ester side chain length of polymers and copolymers, the greater the water repellency, the greater the flexibility and the more they are capable of accommodating dimensional changes.[9]

Reactive monomeric diluents used in UV-curable coatings can be grouped into monofunctional, di-, tri-, tetra-, and penta-functional monomers. Some of the more widely used reactive diluents include the following:

Vinyls

1. Styrene, alpha-methyl styrene, and vinyl toluene. These materials are low in cost, possess good hardness, are slow to cure, are volatile, and copolymerize rather well. Styrene T_g = 212°F; volatilization rate = 19 mg/min.

2. Vinyl acetate. Vinyl acetate is an excellent viscosity reducer but is flammable and has a high vapor pressure. Formulations containing this compound have poor weatherability and are water sensitive. T_g = 86°F; shrinkage = 21.7%.

3. N-Vinyl pyrrolidone. This monomer has excellent viscosity reducing characteristics and is low in toxicity and gives improved flexibility to the cured coating.

Acrylics

Monoacrylates.

1. n-Butyl acrylate. Possesses slow cure and poor solvent resistance and is volatile, although it is a good viscosity reducer and improves flexibility to the cured coating. T_g = -71°F; volatilization rate = 17 mg/min.

2. 2-Ethylhexylacrylate. Most widely used diluent and has properties very similar to n-Butyl acrylate, except it is not as volatile. T_g = 114°F; volatilization rate = 0.5 mg/min.

3. Isodecyl acrylate. Has good viscosity reducing properties, low volatility and contributes to increased flexibility. Volatilization rate = 0.08 mg/min.

4. Iso-bornyl acrylate. Has fast cure rate, low shrinkage, low toxicity, high hardness and low volatility but has a strong odor associated with it. Shrinkage = 8.2%; volatilization rate = 0.2 mg/min.

5. Phenoxyethylacrylate. Has excellent viscosity reducing characteristics.

6. Tetrahydrofurylacrylate. Has excellent viscosity reducing properties but has a strong odor and is relatively more reactive than other acrylates limiting the shelf-life of many UV-curable systems.

7. 2-Hydroxyethylacrylate. A good viscosity reducer but is highly toxic.

8. 3-Hydroxypropylacrylate. A good viscosity reducer but is highly toxic.

9. Ethoxyethoxyethyl acrylate. Has high reactivity, low odor, and low volatility. Viscosity at 25°C = 5 cps.

Diacrylates

1. 1,4-butane-diol diacrylate
2. Neopentyl glycol diacrylate. Shrinkage = 14.2%; volatilization rate = 0.07 mg/min; b.p. = 122°C at 2 mm; viscosity = 32 cps at 25°C.
3. Diethylene glycol diacrylate
4. 1,6-Hexanediol diacrylate. Volatilization rate = 0.02 mg/min; viscosity = 36 cps at 25°C.

Items 1-4 are good viscosity reducers, their cross-link density is low, but many have dermatitis and toxicity problems. Item 2 imparts a high degree of thermal and oxidative stability to polymers because of its structure.

Triacrylates

1. Trimethylol propane triacrylate. b.p. = over 200°C at 1 mm; viscosity = 148 cps at 25°C.
2. Pentaerythritol triacrylate. High-b.p. liquid; viscosity = 800 to 1000 cps at 25°C.

Tetra-Acrylates

1. Pentaerythritol tetra-acrylate

Penta-Acrylates

1. Dipentaerythrital (mono-hydroxy) penta-acrylate

Allylic Monomers

1. Triallyl cyanurate
2. Trimethylol propane triallyl ether

Typically, the choice of monomer diluents that are used in the coating formulation can control many of the UV-cured coating properties including T_g, modulus, elongation, hardness, flexibility, cross-link density, application viscosity and cure rate of the system. Generally, as the functionality of the reactive diluents increase in the coating formulation, the modulus increases and the elongation decreases. This is to be expected due to an increase in cross-link density resulting from using diluents with increasing functionality.[5,10-13]

Photoinitiators

Photoinitiators are the driving force of the coating system and absorb UV radiation between 300 to 400 nm followed by dissociation into initiating species including free radicals, acids, anions, or cations. This discussion will be limited to free radical producing photoinitiators which make up the majority of UV-curable systems currently used for optical fiber coatings.[5,7,14]

The free radicals that are generated subsequently interact with monomers or acrylate terminated oligomers initiating polymerizations. The degree of polymerization and the physical properties of the UV-cured coating is dependant on the type and concentration of the photoinitiator.[5,14]

It has been reported that microbending losses can result in germanium and phosphorus doped silica fibers after exposure to short UV-wavelength radiation. However, using photoinitiators that absorb strongly below 360 nm can significantly reduce this damage.[2]

Some of the more commonly used photoinitiators and their characteristics are described below.

1. Halogen Substituted Acetophenones. These materials are typically chlorinated and can generate corrosive hydrogen chloride.

2. Diethoxyacetophenone. This material is a liquid and generally gives clear coatings.

3. Benzoin and Benoin Ethers. These materials were some of the first photoinitiators to be used. The efficiency of these compounds appears to be system dependent.

4. Alpha Acyloxime Esters. Are more efficient than 2 and 3 but are unstable in acrylate systems and usually cause the coating to yellow.

5. Benzyl Ketals. Newest and most commonly used photoinitiator.

6. Acylphosphine Oxide. These compounds are low yellowing in cured coatings, but are known to reduce the pot life of uncured coatings.

7. Substituted Alpha Amino Ketones. Relatively new compounds that have been shown to be efficient in thin coatings and inks.

8. Benzophenone. Are hydrogen abstracting initiators that require a source of abstractable hydrogen (i.e., alkyl amine) to be effective photoinitiators. Their efficiency is not affected in the presence of oxygen as are some of the other photoinitiators.

9. Michler's Ketone. Used in pigmented coatings and UV-curable inks.

10. Thiolene Photoinitiation. Thermoplastic or thermoset properties are produced depending on the prepolymer structure.

11. Diaryliodonium Salts. Are generally used for cationic polymerizations, but in the presence of hydrogen donors (i.e., amines or secondary alcohols) they produce radicals which are capable of initiating radical polymerization.

12. Glyoxyl Esters. Gives clear cured coatings.

Quenching or the reduction of the rate of free radical polymerization by oxygen (oxygen inhibition) can effectively be minimized by curing the coating in the presence of an inert atmosphere. Other techniques that may be more practical include using a high concentration of the photoinitiator (note: this will increase the cure rate, but may reduce the potlife of the resin) or increasing the UV light intensity. In addition, the use of a high concentration of multifunctional acrylates, dye sensitizers or surface active initiators has been shown to minimize the effect of oxygen. Some UV-curable coatings are more sensitive than others with regard to oxygen inhibition and attention should be given to preventing this undesirable process from occurring since it potentially determines the degree of cure or lack thereof.[5,6,14]

Inhibitors

UV-curable formulations also contain small quantities of inhibitors that serve to prevent the initiation of the free radical polymerization reaction during processing and storage. Excess amounts of these materials must be avoided since it has been reported to seriously affect the degree of cure of the coating.[5]

Other Additives

Other additives may be added to coating formulations to control the flow during application, the surface properties and the adhesion. In addition, nonreactive polymers and chain transfer agents may also be present in coatings. The decision to incorporate these additives into the coating formulation should be carefully weighed against the potential long-term problems that may result because of their use. Some of the adverse effects might involve a degradation in the strength or fatigue characteristics of the fiber, coating and/or adhesive as a result of an increased level of water absorption or the migration of additives over time (some additives are more hygroscopic and/or migrator than others).[5]

Coatings which involve an evolution of hydrogen should be avoided. It has been reported that hydrogen can diffuse into the core of the fiber and significantly degrade optical transmission. Hydrogen is capable of participating in irreversible chemical reactions with the silica core resulting in the formation of silanol, silicon hydride and/or phosphates (phosphorus is present as a dopant material in some core materials). Hydrogen may also undergo reversible migration into the core where it may occupy interstitial defects in the silica molecular structure. Thermally cured silicones have been reported in the literature to produce hydrogen after reaction with water.[4]

RECENT STUDIES ON ULTRAVIOLET-CURABLE COATINGS

An interesting paper was published in 1979 on the *Effects of Water and Moisture on Strengths of Optical Glass (Silica) Fibers Coated with a UV-Cured Epoxy Acrylate*. This study focused on the tensile strengths of optical fibers that were subjected to three different environments including (1) water, 22°C; (2) 90% relative humidity, 32.6°C; and (3) 50% relative humidity, 22°C. The results of these studies conducted over a 36-month period showed a progressive decrease in strength of specimens exposed to both the water and 90% relative humidity environments. Aging of the optical fibers in an atmosphere of 50% relative humidity over the same length of time showed no reduction in fiber strength.[15]

In 1985, Hussain subjected optical fibers coated with different UV-curable coatings to various temperature and humidity conditions and studied their relative rigidities using a torsional pendulum as a function of temperature, humidity and UV lamp intensity. His study concentrated on one technique that is useful when one is attempting to determine the suitability and important processing parameters of UV-curable coatings.[16]

A modified differential scanning calorimeter was recently used as a quality control technique to determine the reactivity of incoming uncured UV-curable coatings. This technique may also be useful as a test method for determining the degree of cure of UV-curable resins during the coating process.[17]

A recent paper by Bram describes the advantages and disadvantages of various test methods that are currently being used by the pulp and paper industry for determining the degree of cure of UV-curable coatings. These methods include: press-side tests, solvent resistance tests, Tabor abrasion tests, slide angle tests, Sutherland rub tests, permanganate stain tests and adhesion tests.[18]

In 1977 Bell Laboratories proof tested a large number of optical fibers coated with a UV-curable epoxy-acrylate coating. Through SEM studies, they concluded that a large percentage of failures could be attributed to fiber surface contaminants that were originally present in the drawing facility. These contaminants apparently were from the furnace components. Similar testing after laser drawing showed no evidence of contaminants.[19]

Levy and Massey reported in 1981 on the effect of compositional changes on the mechanical properties of UV-curable coatings. Specifically, they studied a urethane diacrylate oligomer system containing two monomeric reactive diluents (2-ethoxyethoxyethyl acrylate-EEEA and N-vinyl-pyrrolidone-NVP) and a photoinitiator (2,2-dimethoxy-2-phenylacetophenone). They concluded that the modulus, tensile strength, and elongation of the cured coatings decreased with increasing concentration of EEEA and that these mechanical properties were independent of the compositional changes that were made with the urethane diacrylate (71 to 78%) and/or the NVP (0 to 23%). Apparently, as the concentration of the more reactive EEEA is increased, there is a preferential reaction that predominates during cure that results in an overall decrease in the cross-link density of the cured coating. In addition, they concluded that in order to produce homogenous UV-cured coatings, one must use monomers and oligomers that have approximately the same degree of reactivity.[20]

In 1982 a study was conducted on nine different UV-curable polyester acrylates using polyethyleneglycol diacrylate (PEGDA) as the reactive monomeric diluent and benzil dimethylketal as the photoinitiator. The results of this study included the following:

1. UV exposure times decreased with higher number average molecular weight (Mn) of the polyester acrylate during cure in ambient atmosphere. In an inert atmosphere there was no dependency on Mn.

2. The higher the functionality of the polyester acrylate, the shorter the exposure times and the higher the cure speeds (meters/minute).

3. The higher the viscosity of the polyester acrylate, the shorter the exposure time and the higher the cure speed under ambient atmosphere. Curing under inert conditions showed no dependency on viscosity.

4. Although under an inert atmosphere a hard coating can be achieved at shorter exposure times, the degree of cure is lower compared with an equal exposure time in air. Therefore, to increase the degree of cure in an inert atmosphere to the same level as in the ambient atmosphere, the exposure time has to be increased, thereby obviating most of the advantages of curing in an inert atmosphere.

5. The curing speed can be increased by matching the absorption spectrum of the photoinitiator system to the UV-lamp spectrum.[7]

Ampex Corporation published an article in 1983 concerning an investigation on abrasion-resistant UV-curable coatings. Their study was restricted to copolymers of pentaerythritol triacrylate and trimethylolpropane triacrylate with various acrylic or vinyl monomeric diluents and several different photoinitiators. Their conclusions were that the pentaerythritol triacrylate systems were faster curing, exhibited better abrasion resistance (using DuPont's steel wool rotary test) and had higher viscosities relative to equivalent trimethylolpropane triacrylate systems. Of all the photoinitiators that they studied, para-phenoxydichloroacetophenone was the most effective.[21]

STORAGE/AGING ON BOBBIN

The key to the operation of the FOG-M missile is the fiber optic data link between the flying missile and the ground-based operator. This link provides the operator with a missile's eye view of its forward field and allows in-flight course changes and target selection to be made during Non-Line-Of-Sight (NLOS) firings. The optical fiber is a single mode fiber stored on and payed out from a bobbin in the rear of the missile. Currently, this link is ~10 km in length and wound on a tapered mandrel in a double-tapered configuration. The fiber winding on the mandrel is done in a very precise manner with the optical fiber layers arranged to produce a close packed hexagonal configuration. An adhesive is applied over each wound layer to bind the layers together and to add to the stability of the wound spool. This winding system has been satisfactory in initial test firings of the missile. Questions, however, remain as to the long term stability and performance of the wound bobbin. The Army requires that the payout performance of the fiber optic link continue to be satisfactory after long periods of storage and under adverse field conditions. The principal factors affecting long term, adverse condition stability are temperature variations, moisture levels, and mechanical vibration/shock. The production fibers, adhesives and winding systems are not established at this time. Nevertheless, the materials and fabrication concepts are known to a great enough degree to allow an assessment of the long term risk and the consideration of issues that should be addressed to minimize these risks. The remainder of this section addresses these risks and attempts to establish a philosophy for establishing the degree of seriousness to the performance of the bobbin payout system.

The issue basic to determining the long-term performance and reliability of the wound bobbin is identical to that surrounding any system which must continue to perform over long periods. That is, how does one accelerate the changes that might occur over

time in such a manner as to simulate failures early enough to build in corrections or predict failure rates. It is an age-old problem—whether dealing with an automobile, a 737 airplane, or the tip on a ball point pen. The difficulty of the problem and the likelihood of a less than perfect answer should not, however, prevent a realistic assessment. Knowledge from similar applications, from similar material and from independent sources can be most valuable in keeping the assessment realistic. The "unknown unknown" can't prevent action from being taken. A procedural approach must be adopted.

The first step in addressing the bobbin aging issues should be to establish what form failure of the bobbin to deploy satisfactorily in flight would take; i.e., what must the deploying bobbin do in flight and what will prevent it from performing, and what are the consequences of failure. In discussions with persons and organizations knowledgeable about this application, we have come across many viable questions and concerns. We are not, however, aware of any failure to deploy that has been tied to these concerns. Each issue (or combination of issues) should be addressed as to probability of occurrence and impact. Ideally, a failure should be able to be demonstrated. Once this activity is complete, it is a reasonably straightforward process to plan actions to mitigate the consequences of a failure. Many ancillary issues are involved (such as funding availability, contractual constraints, time availability) but choices can be made with full knowledge of the risk incurred.

Two general areas of concern have been raised by staff at MICOM. These are effects of thermal mismatch between the bobbin mandrel and the optical fiber and the effects of adhesive(s) aging including compatibility.

The adhesive aging/compatibility issue is be addressed in another section. A discussion of our view of the thermal mismatch issue follows.

THERMAL MISMATCH

The concern about thermal mismatch between the bobbin mandrel and the optical fiber arises because of differences between coefficients of thermal expansion (CTEs). The fiber is precision wound on the mandrel at room temperature (current practice) but, subsequently, must withstand temperature excursions in the ±100°F range. If the mandrel shrinks away from the fiber, the entire package could become loose and the build be destroyed. If the mandrel shrinks away from the fiber, the entire package could become loose and the build be destroyed. If the mandrel grows into the bundle build, the fiber could be overstressed or be pushed out the ends of the build with similar consequences. Both of these scenarios are possible and the likelihood of either happening increases with temperature cycling. We do not know if the failure has been simulated in the laboratory.

In principal, it seems rather straightforward to calculate the stresses on the optical fiber package due to expansion of the mandrel or to calculate the temperature difference necessary to cause the package to become loose. In practice, it is not. The mandrel, which is currently made from aluminum, presents no problem as this is a well known material. Over the temperature range being considered, aluminum has a nearly constant CTE and the temperatures are not high enough to affect temper. The fiber optic bundle

is quite another story. The optical fiber itself is a composite of several materials (the core, cladding, and one or two buffer layers). The linear expansion of the fiber in the direction of the winding is probably controlled by the expansion of the core and cladding which for this purpose are the same material. No specific data could be located but it is expected that it would behave more like quartz than borosilicate glass. The buffer(s) are low T_g materials and will be very viscoelastic in the temperature range of interest. Similarly, the adhesive used to hold the bundle together will be viscoelastic. Finally, the closed-packed hexagonal structure of the bundle probably contains some free space even with the binder adhesive in place. It is reasonable to assume that stress increases calculated using just the CTE of quartz would be reduced through the compliance afforded by the buffers and adhesive layers.

Lateral forces on the optical fiber bundle generated as a result of a temperature increase are seen as the most probable cause for the bundle to deform. At elevated temperature, the buffers and adhesives are very soft (discussed elsewhere) and may even flow. The buffer-to-adhesive bonds are intentionally not strong and through repeated temperature cycling or in the presence of vibration may allow the bundle build to collapse. Payout at elevated temperature may also be unreliable if the adhesive to buffer bond strength is important to the stability of the motion.

As we stated, we don't know if the bobbin will experience failures due to the above concerns. This issue needs further investigation and more will be said later about how we think this can be approached. One solution that has been proposed and investigated to some degree by the MICOM staff is to make the mandrel from a composite material. In as far as the problem stems from thermal mismatches, composites do appear to be able to correct the thermally generated forces. Since we view the fiber bundle as a composite with significantly different properties in the lateral and circumferential directions, composites offer the ability to be tailored to behave similarly. It is doubtful that a composite mandrel can be produced with the same initial cost as an aluminum mandrel, but it still may be cost effective if failure rates are reduced and reliability improved. Even though the exact materials to be used in the optical bundle are not known, they are known by generic class and this provides enough information to begin analysis and testing.

HANDLING EFFECTS PRIOR TO DEPLOYMENT

Damage to an optical fiber between the time the fiber is produced and the time it is on the bobbin mandrel ready for payout can result from improper storage and handling of the fiber spool or from the winding process itself. Here, at ORNL, we do not have a great deal of experience handling large quantities of optical fiber, but we do have an extensive background with handling and processing coated glass fiber. This type of fiber is not completely analogous to an optical fiber, but many of the precautions followed and damage mechanisms observed can be considered when assessing the risks associated with handling optical fibers during intermediate processing.

As manufactured, glass fibers have a characteristic strength established by the quality of the fiber drawing process. The fibers are very susceptible to handling and

environmental damage and are coated with a sizing agent (in the case of fiberglass) or buffer (in the case of optical fibers). A major purpose of this sizing is to protect the glass fiber from corrosion by moisture or mechanical damage from handling. The potential for this type of damage is so great as to require the fiber to be protected immediately after being drawn. By and large, these coatings effectively do their job. The effectiveness can be degraded if the coating "ages" or is not uniformly applied (see separate section for information on aging of optical fiber coatings). Rough handling can, however, still damage or even break the protected fiber and careful consideration of protective measures is necessary at all times.

The first consideration is the amount of coating put on a fiber (assuming uniformity). For fiberglass filaments, too much coating can have a detrimental effect on a fabricated composite. Too little coating can be ineffective in protecting the fiber during processing and cause breaks or fuzzing of the filaments. The balance is delicate and the coating level must be chosen with full evaluation of subsequent processing requirements. Most probably, in the case of an optical fiber payout package, the bobbin-winding process will have to be developed in such a manner as to accommodate the optical fiber as delivered by the manufacturer. Manufacturing needs for the fiber, considering the need to prevent damage at that stage and necessary information transmission qualities, will not be driven by the bobbin winding process. The only difficulty foreseen will be that of accommodating fibers from more than one manufacturer in a given process.

Once drawn and coated, fibers must be packaged for transport to the end user or bobbin winder in this case. It is highly desirable to minimize the amount of handling which occurs. The drawing package and the winding package must be the same. Coordination between the fiber producer and the bobbin winder will be necessary in order to make this a success. In the fiberglass industry, the development of a package common to the producer and the user has long been a goal. It has been only successfully accomplished in a few instances. The ordinary method requires the use of an intermediate package during drawing and the subsequent production of a specialized package for the end user.

Just as important as the drawing/winding package is the shipping container used to transport the fiber. A variety of schemes are employed in the fiberglass industry depending upon the criticality of the end use. A shipping container for critical use would provide positive support for the package while not making contact with the fibers themselves. Shrink wraps, moisture barriers, opaque covering and other protective materials are usually used to prevent damage or to retard a known aging process.

Given that the fiber can be adequately protected by its packaging, the most likely place for damage to occur is during the bobbin winding process. This process requires that the fiber be tensioned and passed over contact points that may abrade the protective coatings. It has already been recognized that the number of contacts need to be minimized and that pulley sizes and degree of wrap need to be carefully controlled. In a production process, where winding speeds are higher, these considerations will become more critical.

OPTICAL TRANSMISSION

EFFECTS OF MICROBENDING AND MACROBENDING ON SINGLEMODE OPTICAL FIBERS.

For several types of singlemode fiber, the *modal power profile* or near-field intensity pattern approximates a Guassian

$$p(r) = p(0)\ \exp[-2(r^2/w_0^2)]\ ,$$

where $2w_0$ is the *mode-field diameter* (MFD). This is shown for a step-index case in Fig. 1, where it is apparent that the intensity at the mode radius $r = w_0$ has reduced to the $p(w_6)/p(0) = e^{-2}$ or 13.5%; moreover, a fraction, e^{-2}, of the power resides beyond the MFD.

Next consider a bend of radius R, illustrated in Fig. 2. Note the mode power profile skews slightly away from the bend. Moreover, a refractive index distortion may occur due to bending stresses. More important, the *mode phase index*, n_p, in the plane of the bend decreases away from the fiber center, because in that area, the field must travel faster to preserve the cross-sectional phase. This requires that

$$n_p(r) = n_p/[1 + (r/R)]\ .$$

The field will attempt to exceed the cladding phase velocity beyond a distance,

$$r_o = R(n_p - n)/n.$$

The field beyond this point will thus radiate away. Good bend resistance is achieved with fiber designs of small mode diameter ($w_0 < r_0$) and a large phase index difference, n_p-n, between the mode and cladding. This is achieved with a small core radius, a, and a large core and cladding refractive-index delta, but with care not to dispersion-shift the fiber or increase scattering losses. Fibers are increasingly sensitive at longer wavelengths because w_0 grows, while r_0 shrinks.

In practice, after a singlemode optical fiber has been bent to a *minimum bend radius* approximately ten times its buffer diameter, it begins to dissipate core-guided light into the cladding. As the optical fiber is further bent, it attenuates additional light until it fractures (at a raJius approximately one-half the minimum bend radius). Thus, for a 250-μm-buffered fiber, the radius at which attenuation begins is ~2.5 mm, and the *break point radius* is ~1.25 mm. In payout systems, it is necessary to determine the bend-loss characteristics of each specific optical fiber in order to evaluate the system correctly. It should be noted here that the above estimations are dependent on more than just the fiber size. For example, the break-point radius is also dependent on, among other things, the strength of the fiber and the buffer composition.

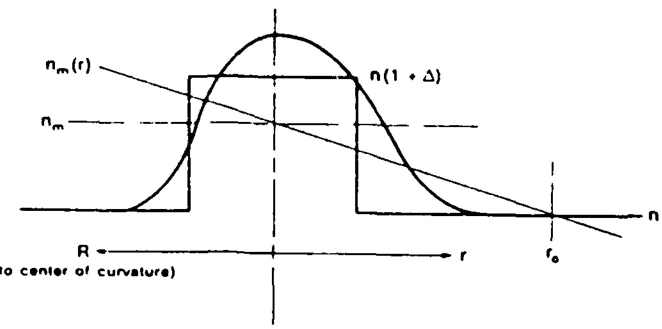

Fig. 1. Mode profile of electromagnetic radiation propagating through a step-index singlemode optical fiber at a bend located in the fiber as a function of radial distance outward. (Lin et al.[42])

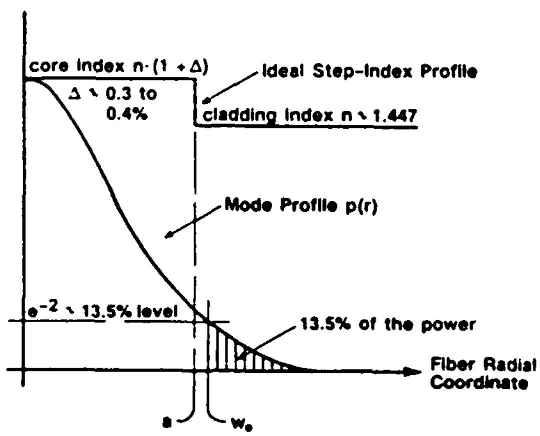

Fig. 2. Mode profile of electromagnetic radiation located in the cladding of a step-index singlemode fiber as a function of radial distance outward. (Lin et al.[42])

Several fiber manufacturers have a minimum bend radius specification prior to attenuation. For instance, Corning states that their minimum bend radius is ~0.010 in. During the past few years, two types of singlemode fiber have become widely available, namely, matched-clad, and depressed-clad singlemode fibers. The depressed-clad fiber, originally developed and patented by AT&T, contains a cladding having a region where the refractive index is reduced in value. This creates substantially improved bending performance. Thus, if not already in use, it is anticipated that a fiber such as AT&T's depressed clad fiber may be of some additional value to FOG-M system engineers. Often times, however, the couplers used at each end of the fiber optic link are fabricated with matched clad fibers because its simply easier and cheaper to do so. Unfortunately, the MFD for the two types of fiber (matched-clad and depressed-clad) are not identical and, consequently, MFD mismatches are created at connector and/or splice interfaces located between the payout fiber and the coupler pigtail.

It is also important to note that the total losses due to bending will vary from time to time as the payout process takes place, and the loss incurred at the payout crossover point is not necessarily the only microbend loss mechanism. For instance, the physical terrain over which the fiber lays may also induce losses due to bends in the fiber. The microbend losses are also strongly wavelength sensitive. The attenuation at the break-point radius is estimated to be several decibels, although this value will vary with wavelength and type of fiber. For instance, a 1550-nm wavelength source will inherently exhibit higher attenuation values for the same bend radius when compared with a 1300-nm wavelength source.

It would also seem logical to investigate the size of the fiber and how it may be increased or decreased for optimization of the payout system. In most singlemode fibers, a substantial portion of the light travels in the evanescent wave located in the cladding, as discussed above. Consequently, a reduction in the 125-μm's cladding diameter can only be reduced partially. Conversely, it would seem impractical to increase the size of the fiber substantially. An analysis of the optimum fiber size does seem to be warranted, however.

SOURCES OF STRENGTH DEGRADATION IN SINGLEMODE FIBERS

The strength of an optical fiber generally is established during the preform fabrication and the optical fiber drawing processes. Consequently, it is difficult to retain high strength values over several kilometers. If lengths of optical fiber >15 km are required for tethered weapon applications, fusion splicing may be required in order to obtain proof testing specifications >400K psi. Consequently, testing of fusion splice strength will be required as will testing of splice strength degradation over an extended lifetime. The splice locations will also require uniform recoating of the buffers to ensure that the optical fiber lays properly in position during the winding phase of the bobbin assembly. This will not be a trivial task. Also of concern is the fact that even under initial proof testing of 400K psi, and optical fiber's strength will generally degrade over time, i.e., the same fiber will become weaker. Also, as the length of the optical fiber increases, the probability of strength degradation along the fiber increases. Simply stated, the longer the fiber, the higher the likelihood it will break. It should also be noted that

during battle, flying debris from explosions may either weaken or fracture the exposed optical fiber during the payout process.

OPTICAL POWER BUDGET CONSIDERATIONS IN FOG-M FIBER OPTIC LINKS

The optical power budget of a fiber optic link provides a convenient way to analyze and quantify losses. To properly design a fiber optic link, knowledge of all loss mechanisms in the system is required. We have mentioned above, a few of the more prevalent loss mechanisms. Other constraints on the power budget include laser-to-fiber coupling losses, fused biconically tapered coupler insertion and excess losses, connector and/or splice losses, and spectral attenuation. Figure 3 illustrates a graphical representation of a typical power budget which might be applicable to FOG-M applications. In this figure, notice the various loss mechanisms as mentioned above. Figure 3 is, however, misleading because radiation and microbend losses may vary from location to location along the optical fiber and are also time-dependent in nature. For instance, if an extremely intense radiative source is present near the fiber for a short duration, the losses incurred may make communication between the transmitter and receiver impossible for a short length of time.

OTHER SOURCES OF OPTICAL SYSTEM DEGRADATION

The use of epoxies in the manufacturing process of the fused biconically tapered couplers employed at both ends of the fiber optic link is also of concern. These devices do exhibit a specific shelf life and are on the average much more vulnerable to shock, vibration, thermal stresses, etc. than the payout optical fiber itself. Furthermore, at the evanescent wave-coupling region of the coupler, a fiber optic buffer can not be applied due to the coupling characteristics internal to the device. Careful evaluation of each coupler vendor is suggested, and confidential technical reports on their manufacturing process and environmental testing should be mandatory. In addition, government-sponsored "nonbiased" coupler testing is recommended because the Fiber Optic Test Procedures currently available are not specifically related to tethered weaponry.

We do not have knowledge of the bonding and/or fixturing technique used in pigtailing the laser diode sources to the singlemode optical fiber for FOG-M applications. Some techniques currently used in industry do require epoxy-based materials and should be analyzed as possible failure mechanisms. If necessary, similar testing suggestions are recommended for laser pigtailing vendors as were recommended for couplers.

RADIATION EFFECTS AND HARDENING

During a military engagement involving the use of tactical nuclear weapons, fiber optic guided missiles will be exposed to direct radiation, fallout radiation (fission product radiation), and shock effects. The sequence of events from any nuclear explosion is always

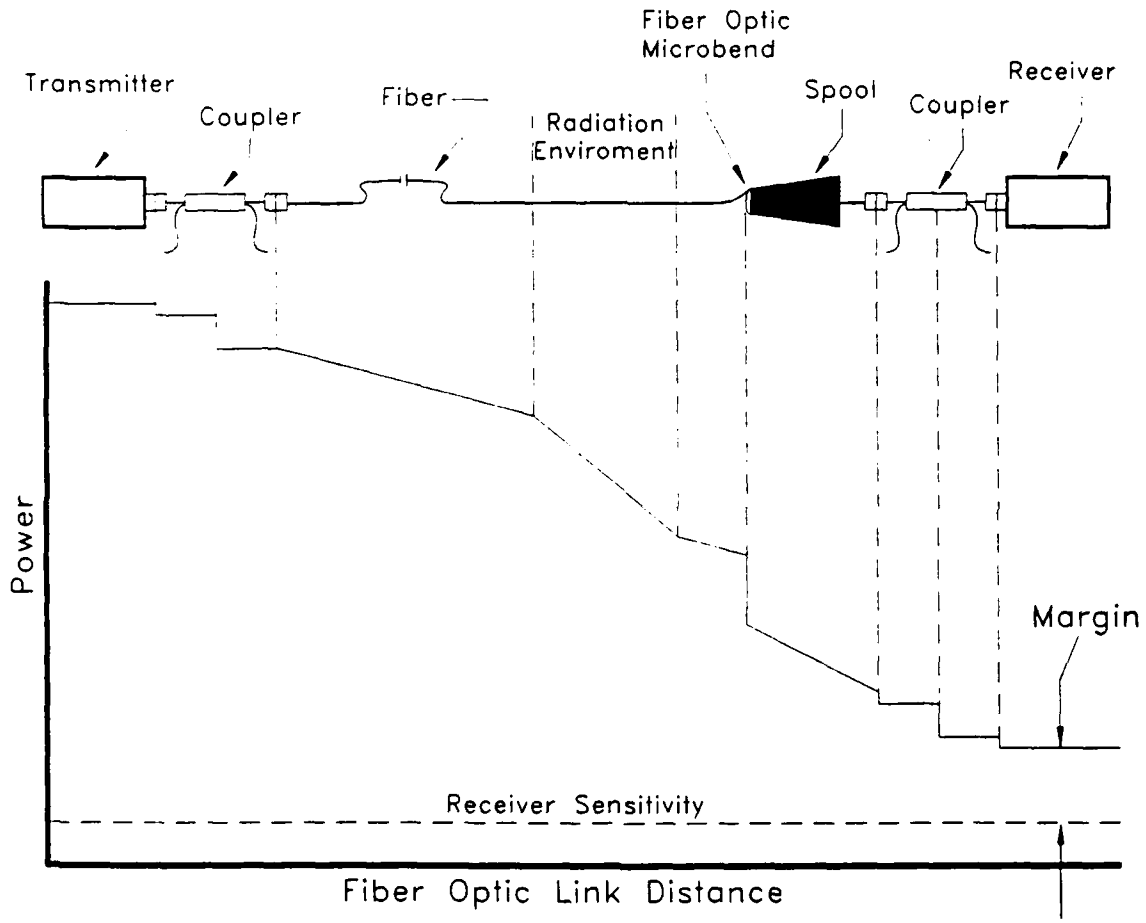

Fig. 3. Estimated power budget of a typical FOG-M fiber optic link.

(1) direct radiation, (2) shock, and (3) fallout radiation. The fission product effects actually occur very early, but they are widely distributed; later settling of clouds and dust brings the fission product emissions closer to the earth, hence the term "fallout." Where many nuclear explosions have occurred in the same area, it would be expected that the fallout component would be established as a more or less constant background effect, with pulsed radiation and shock impacts occurring from time to time.

Fiber optic guided systems operating in such an environment are at considerable risk because, unlike suborbital or orbital guided systems, they must be launched and fly through a large part of the approximate environment in which they will be detonated. To continue to perform as defensive and deterrent systems, preventing the advance of tactical forces, the fiber optics themselves, as well as the mechanical and control systems within the missile, must survive in all but the most extreme conditions. The most extreme conditions are those in which few if any mechanized devices could survive, and can be approximately defined as (1) within a few hundred yards of a nuclear explosion, producing both severe radiation and shock effects, (2) in a high-density debris cloud that produces kinetic effects greater than the tensile strength of the fiber optics, (3) in extreme visual and/or atmospheric conditions, caused either by meteorological effects or weapons effects. We mention debris and visual/atmospheric disturbances along with radiation and shock effects because it is very likely that all will occur together and will result from use of nuclear weapons. In this section we will discuss only the radiation effects; other sections will deal with the concommitant and collateral effects as well as those produced by non-nuclear weapon scenarios.

DIRECT RADIATION EFFECTS ON OPTICAL FIBERS

The production of energy in a nuclear weapon results from both the fission of heavy elements such as ^{235}U and ^{239}Pu and the fusion of light elements such as tritium and deuterium. The fission events produce associated free neutrons in a spectrum up to around 1-MeV, electrons and a wide spectrum of photon energies, most intense in the hard X-ray range. Fission products are usually radioactive and tend to emit gamma rays in the range around 1 to 2 MeV. Fusion events produce large bursts of 14- and 2.5-MeV neutrons, which, in turn, interact to make many other radiation-producing events.

The effects on optical fibers from direct, or prompt, radiation are primarily from photon flux and neutron flux. Slow electrons, alpha particles and the like are absorbed quickly by the local environment of the blast, and would not be expected to produce a large energy dose upon a long strand of fiber hundreds of meters away. The only likely damage effect from alphas and electrons would occur when fibers are coated with radioactive dust from the area; these effects are from the fallout, not the prompt events.

Prompt neutron flux, especially from the burst of 14-MeV neutrons, will follow the prompt burst of gamma rays, the time separation being a function of the distance to the source. Like the gamma burst, the neutrons will produce radiochromic effects in the fibers, dramatically lowering the transmission for a period of some microseconds. The interaction cross section for fast neutrons, however, in the silica of the fibers will be lower than for gammas, and the pulse will be broadened in comparison with the gammas, so the

optical transmission effects in the fiber will be two or three orders of magnitude lower. Hundreds of microseconds after the nuclear event, thermalized or near-thermalized neutrons will be in abundance in the area, resulting from and causing fallout radiation. Neutron effects are most important in any hydrogenous material or in any material containing boron, cadmium, or other elements with isotopes that have resonant absorption cross sections for low-energy neutrons. The effect of hydrogenous material is simply the rapid slowing of fast neutrons to lower energies where they are more likely to be absorbed. Absorption generates damage effects in virtually any material, especially transparent ones where color centers are produced, causing attenuation of optical transmission.

Studies have been done to determine the attenuation of light in optical fibers from photon flux, usually gamma rays around 1 or 2 MeV.[22-26] Typical numbers for 1.3-μm transmission are around 1 dB/Mrad-cm. This means that a uniform megarad dose on the fiber stretched over a kilometer would produce an attenuation of 100,000 dB, more than sufficient to interrupt operation of a missile video system! Even 1 krad similarly distributed will produce ~100-dB loss, also adequate to disrupt communication; however, fibers tend to recover rapidly from the major attenuation effects, regaining significant transmission after the initial radiochromic effect of the prompt energy. Further, the cross sectional area of a kilometer length of fiber with a jacket diameter of ~0.25 mm is ~0.25 m^2. At 1 km (1000 m) from a nuclear explosion, this solid angle is about two or three times 10^{-7} sr, adequately large to produce kilorad levels or higher.

Recovery times from radiochromic effects are very rapid, typically several orders of magnitude in the time of a video frame (33.3 ms). This is because the radiochromicity is the result of prompt events in the material; when those events stop, recovery begins. However, recovery times from radiation-damaged fibers take much longer, typically hundreds of seconds for a recovery of a factor of 4 or 5 at room temperature.[27] These damage recovery times, however, vary greatly with different fibers, as does the damage accumulation from repeated doses. Additionally, the outside sheathing material, if made radioactive by the prompt radiation, will continue to damage the fiber after recovery.

It is clear that specific data are needed for each of the candidate types of optical fiber and sheathing for use in fiber optic guidance systems. The specific data include (1) prompt attenuations in decibels per kilorad per centimeter or similar units, (2) recovery times in decibels per minute per kilorad or similar units, (3) damage accumulation measurements, giving fiber attenuations in decibels per kilorad, for example, where the radiation is cumulative and the attenuation is permanent (at least for the battle scenario, say hours). All these numbers of course are dependent on the energy of the radiation source. The real source, the nuclear weapon, produces a broad photon spectrum. The best possible data would be those obtained from a specific weapons effects test done at the Nevada Test Site.

In recent years, the effects of radiation on optical fibers has been well documented.[28-39] The results of these studies have concluded that under extreme radiation exposure such as that from electrons, neutrons, and gamma-radiation, optical fibers generally exhibit substantial time-dependent attenuation. This attenuation is a function of several parameters including (1) dose, (2) dose rate, (3) optical fiber dimensions and

composition, (4) temperature, and (5) wavelength. Unfortunately, much of the recent literature relates to multimode optical fiber which is not directly applicable to FOG-M applications. However, Looney et al.,[40] (Los Alamos National Laboratory) recently investigated radiation effects in singlemode optical fiber for the Nuclear effects Task Group reporting to NATO Panel IV/Research Study Group 12. In their work, radiation-induced transient absorption was measured over time ranges from a few nanoseconds to several microseconds. Their apparatus included an HP Febetron Model 706 electron accelerator and associated apparatus. Although the exact details of the experiment can be found in the above-mentioned reference, Fig. 4 illustrates the attenuation in decibels per meter of various singlemode optical fibers operating at differing wavelengths when radiated by a 50K rad, SiO_2 radiation dose. In these experiments, a SPWZ dainichi low-OH content optical fiber preform was utilized for manufacturing purposes.

Researchers at NRL, as well as other laboratories, have also studied radiation effects in singlemode fiber manufactured by commercial optical fiber vendors, some of which are current and/or potential vendors for payout systems. Figures 5-11 illustrate the results of their experiments. While the improvements associated with these fibers has broadened the applicability of singlemode fibers in radiation environments, *the induced attenuation will continue to be a design parameter that cannot be ignored.*

It is our understanding that the Navy has accepted standard singlemode optical fiber as being radiation hard. Furthermore, optical fiber vendors including SpecTran Corporation, AT&T, Alcatel, Corning Glass Works, and Sumitomo are using standard in-house singlemode optical fiber for payout systems with only slight design modifications. Data from the above vendors relating to their radiation hard fiber specifications are given in Appendices A through C, which indicates an increasing interest in radiation hard singlemode fiber. Unfortunately, optical fiber manufacturers are apparently unwilling to devote extensive research and development funds required for low-volume markets such as FOG-M. Consequently, the development required to define the optimum singlemode optical fiber for the FOG-M program may require financial support from MICOM. Assuming all singlemode optical fiber is similar with respect to radiation-induced attenuation, the final requirement necessary to properly evaluate the optical fiber for FOG-M programs is knowledge of the worst-case battlefield scenario.

DIRECT RADIATION EFFECTS ON COMPONENTS

Prompt nuclear radiation from a tactical device will expose electronic and optical components in the fiber optic guided missile itself as it flies through the battle zone. Test data indicate that destructive damage of most solid state components in control systems will occur only with doses of hundreds of megarads. Such doses are unlikely except within the sure-kill range of the device.[27] Temporary or permanent interruption in the component function, however, can occur as a result of the electromagnetic noise pulse (EMP) that attends the prompt radiation pulse. We recommend further investigation both into the extant data and of appropriate test programs for the specific instrumentation in the fiber optic missile systems.

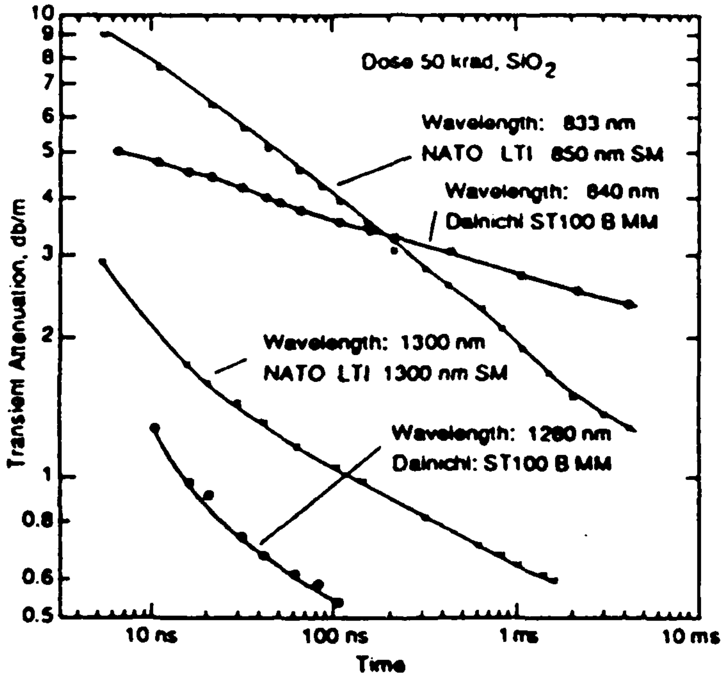

Fig. 4. Radiation induced attenuation as a function of time for various optical fibers. (Looney et al.[40])

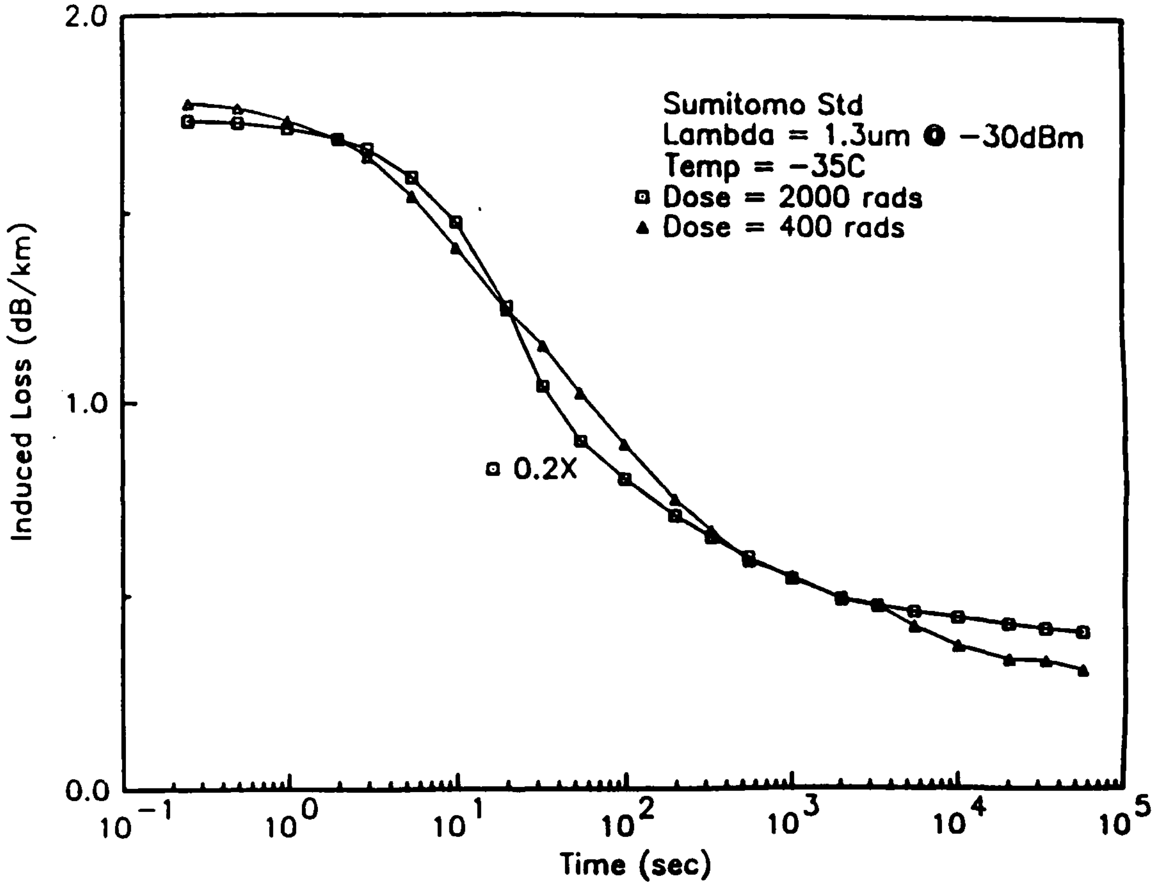

Fig. 5. Recovery of the attenuation induced in a Sumitomo singlemode fiber by doses of 2000 and 400 rads. (Frebiele[28])

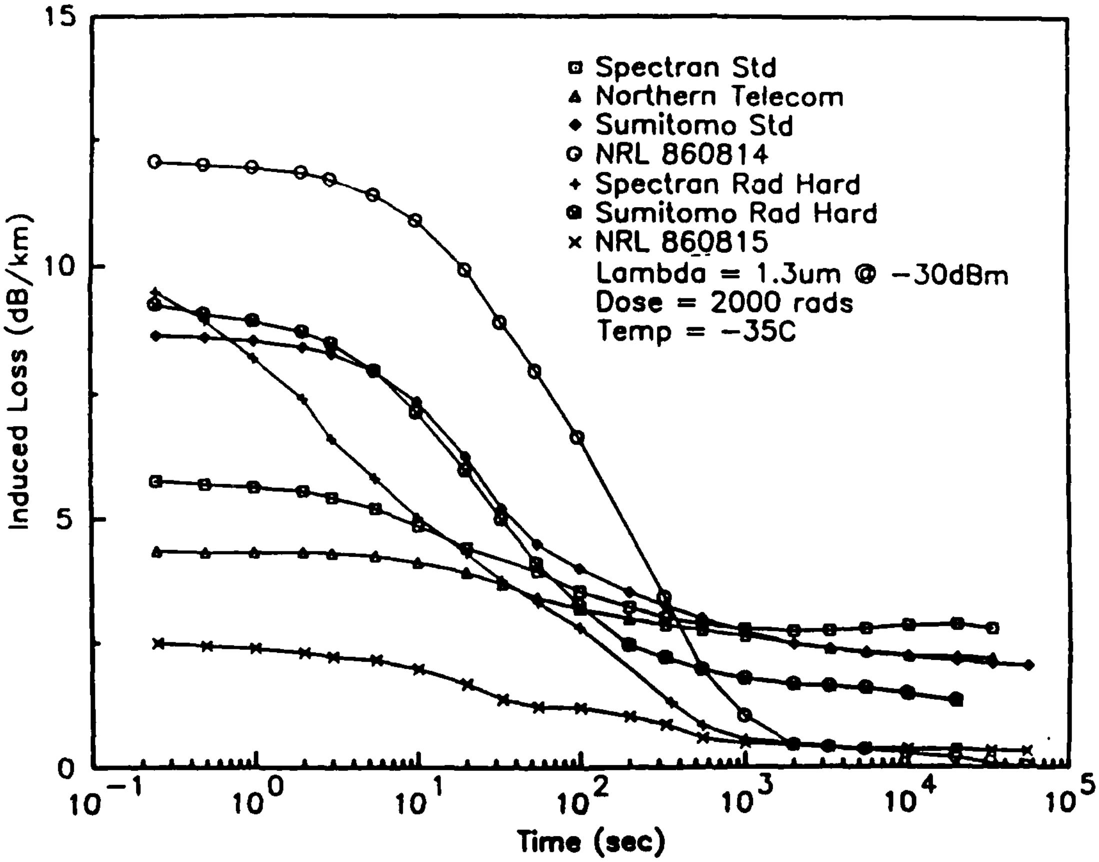

Fig. 6. Recovery Data of Northern Telecom, NRL, Spectran, and Sumitomo singlemode fibers and two NRL prototypes. (Frebiele[28])

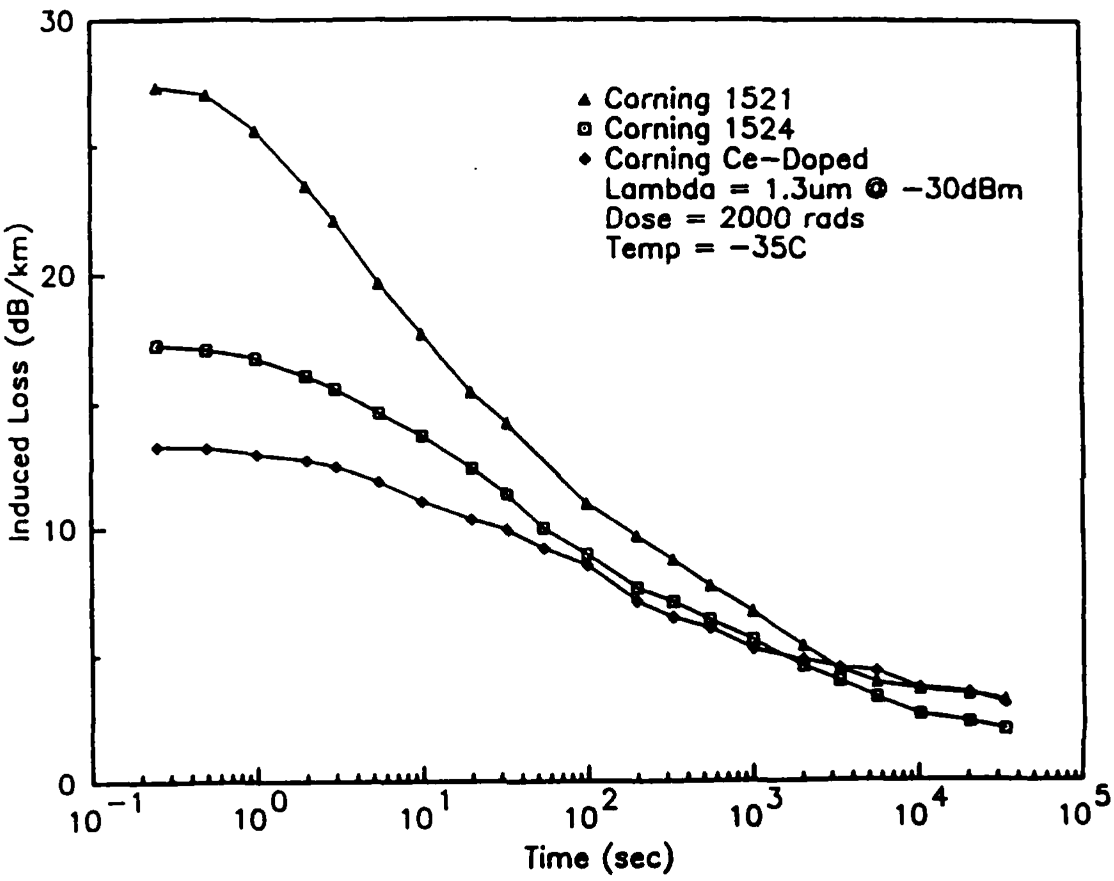

Fig. 7. Recovery data of Corning commercial singlemode fibers. (Frebiele[28])

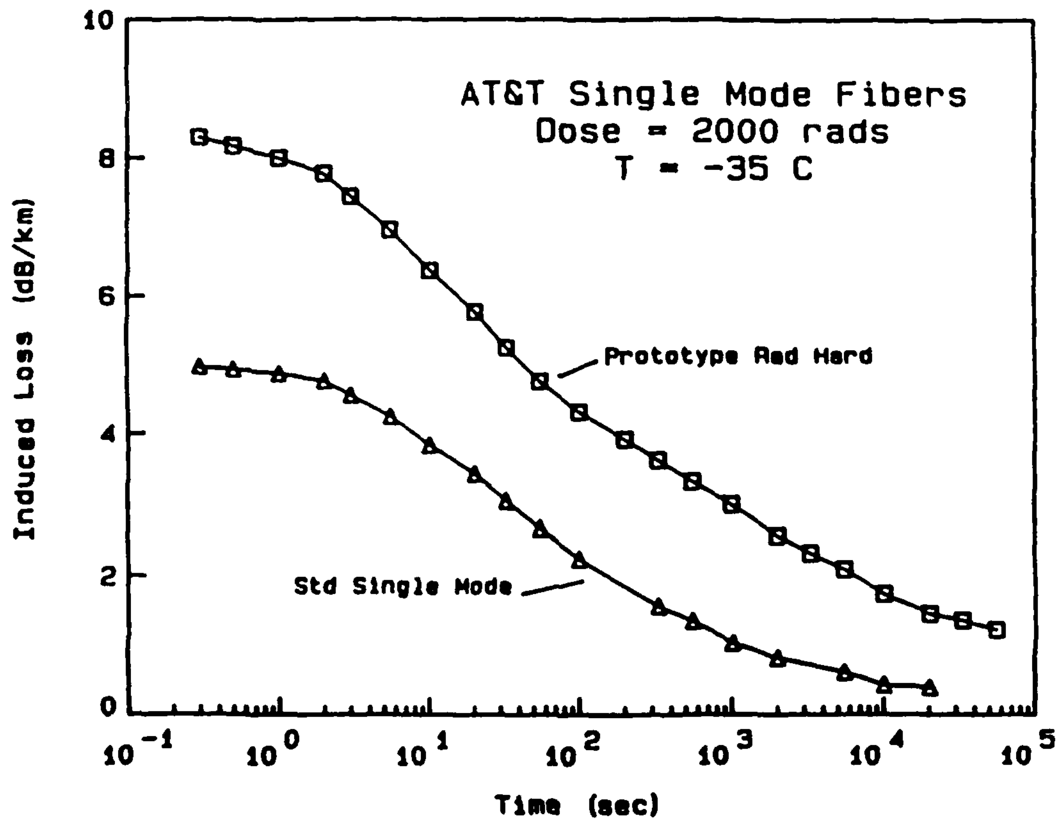

Fig. 8. Recovery data of AT&T standard and rad-hard singlemode fibers. (Frebiele[28])

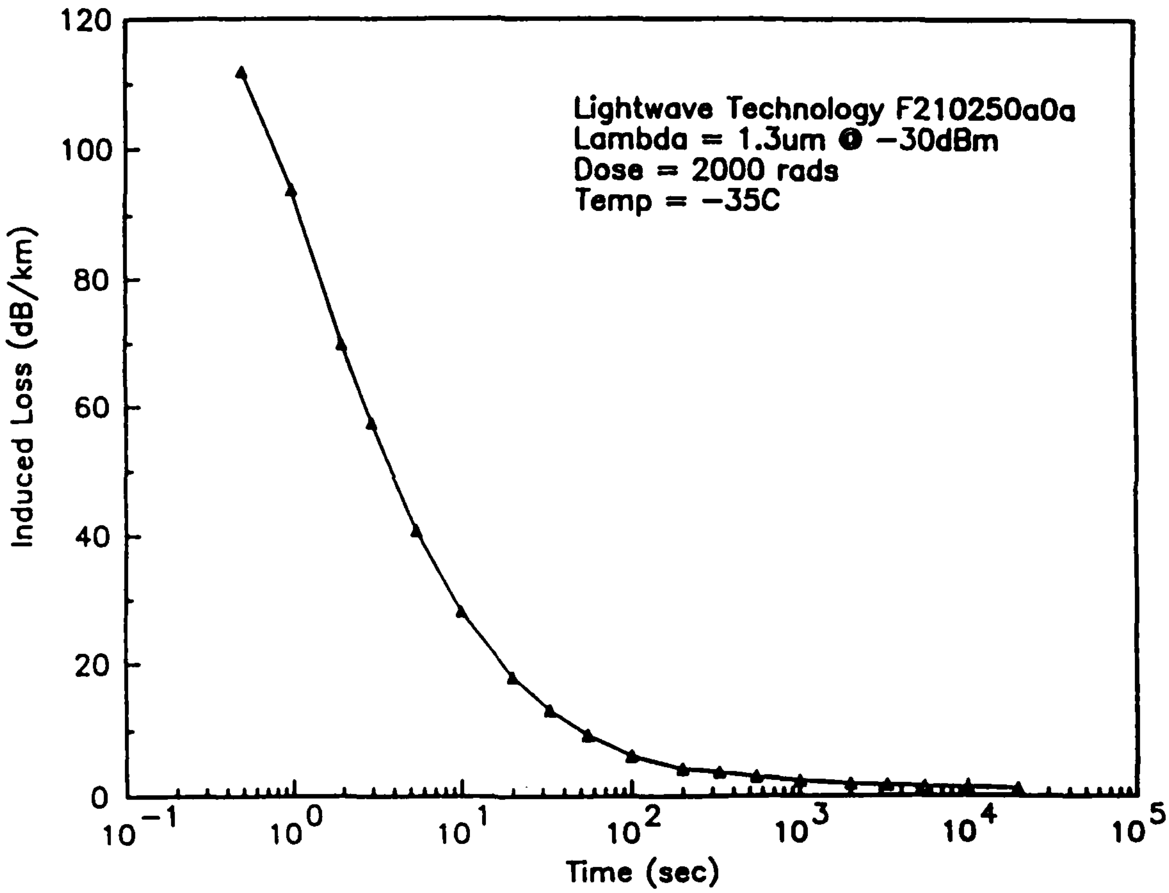

Fig. 9. Recovery data of Lightwave Technologies, Inc., commercial singlemode fiber. (Frebiele[28])

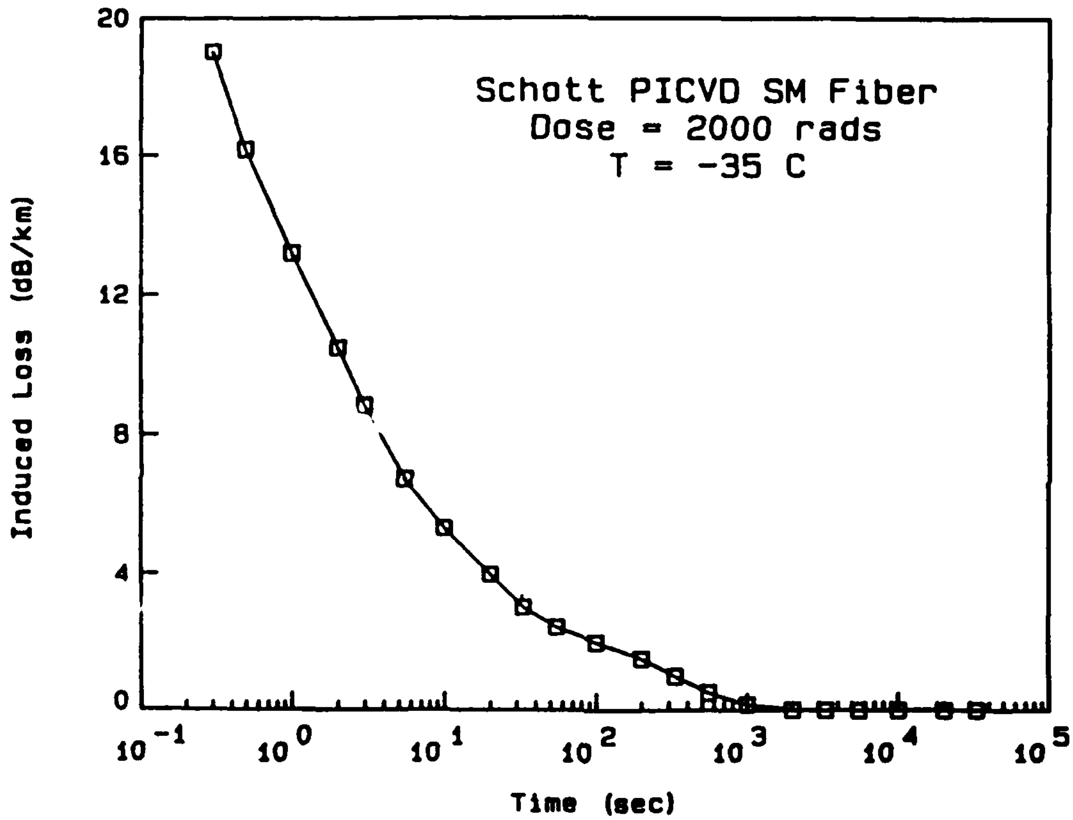

Fig. 10. Recovery data of a Schott commercial singlemode fiber made by the plasma impulse chemical vapor deposition process. (Frebiele[28])

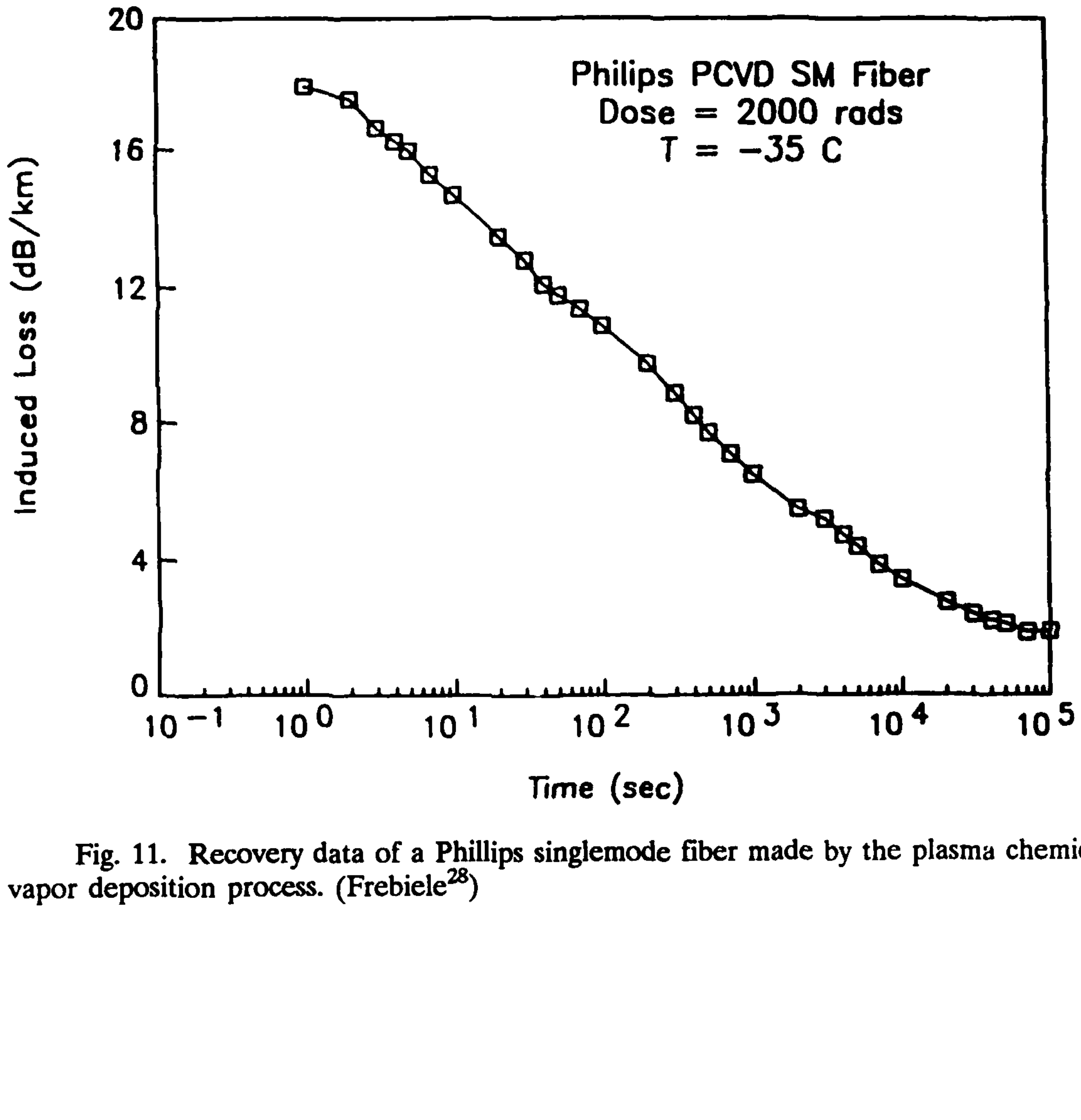

Fig. 11. Recovery data of a Phillips singlemode fiber made by the plasma chemical vapor deposition process. (Frebiele[28])

Radiation shielding for these small, light-weight missiles will be limited, because the most effective shielding against gamma rays and X-rays, the most disruptive types of radiation, requires high-Z mass. Perhaps critical components, possibly already identified, can have small amounts of high-Z material around them. The major shielding for any system should always be distance. Tactical plans for missile use should always take that into consideration when possible. Shielding for EMP is a very different matter. Even a thin layer of conetic or other similar materials will offer some useful protection. All electronic components need this shielding when possible because the disruptive effects can be enormous without it. As for direct radiation effects we recommend a serious study of the extant EMP data and development of appropriate test programs for the specific instrumentation.

Optical components, such as lenses, beam splitters, filters, etc. will be affected by the radiochromic effects similarly to the optic fibers. The detailed differences depend on the specific materials, sizes, and orientations. Again, like fibers, the components will recover quickly from most of the prompt darkening, probably producing no disconnecting interrupt in video sync or signal transmission. True damage effects, however, will be serious and cannot be recovered from in time to matter significantly during the flight. These effects[27] in many instances will be low enough in magnitude to allow the functioning of the missile system, unless the missile is within a sure-kill distance of the device. Here we recommend a more careful evaluation of the data than can be done in this survey, as well as some calibrated measurements for specific components where needed.

It is well known that the most effective radiation shielding for any system is distance. Radiation intensity in virtually all cases decreases with the square of separation distance. Furthermore, shielding and other material imposed in radiation paths, despite any utility, will always produce scattering, reflections, deflections and other distributive processes. Keeping this in mind, and taking advantage of the increased range of the new generation of fiber optic guided systems, it is recommended that modern strategic planning include increased maneuverability and more rapid response in the guidance.

ISSUES NEEDING ATTENTION

FIBER DRAWING

As the FOG-M missile moves into a production program, two issues that have not been addressed during the development phase will have to be addressed. These are the fiber drawing process and the bobbin winding procedure. The manufacture of an optical fiber, uniformly coated without serious defects, in lengths of 10 km or greater will require special attention and qualification activities. In the payout mode, success will be governed by the weakest portion or link. Since it will be physically impossible to subject the entire length of fiber to a proof test, strength above a minimum allowable value will have to be established through statistical means and through very tight process control. Various researchers (see Ref. 41, for example) have investigated the effects of fiber drawing process parameters on the mean strength and variability of the optical fiber. Two of the

most influential factors have been found to be the quality of the starting preform and the drawing environment. Where these factors are not well controlled, the measured strength distributions show a bimodal or trimodal failure behavior. The mean or characteristic strength of the fiber is only slightly affected but, the existence of low strength tails on the failure distributions will ultimately establish the payout reliability of the optical fiber. A process qualification program, an in-process control specification, and product acceptance tests need to be defined that recognize the ultimate use of the fiber in a payout application.

BOBBIN WINDING

The bobbin winding process that we have seen is slow and tedious. The application of the adhesive is a manual process and does not produce uniform fiber-to-fiber bonding in the package. As the system moves towards production, this process will be sped up and the application of the adhesive automated. This actually will provide the opportunity to improve the bobbin package and, if properly done, reduce the degree of in-process inspection required. Again, process qualification, in-process controls and specific product acceptance tests need definition.

FIBER SPLICING

One area that we have not seen addressed is that of how to splice optical fibers together for use in a payout mode. Splices may be necessary to keep the cost of fiber production reasonable or even feasible for 10 to 100 km lengths. The literature does not reveal any activity by fiber manufacturers to establish a continuous drawing process. Ten kilometers seems to be the maximum attainable using finite size preforms. A splice in a payout package must be different than that in a stationary line. In addition to maintaining the information transmission integrity, a splice must be effectively coated so as to produce the same diameter. The package construction will be adversely affected using current methods.

STORAGE EFFECTS ON FIBER AND ADHESIVE

Serious thought should be given to packaging the bobbin in an inert atmosphere (i.e., argon, nitrogen) during its storage life. By packaging the bobbin one may be assured that the potential degradation effects of humidity and any other detrimental chemical compounds present in the surrounding environment (i.e., oxygen, ozone, acidic or basic species, etc.) will pose less of a risk to fiber strength degradation, loss of adhesion, and/or microbending loss of the optical fiber that may occur during long-term storage conditions.

It can be assumed that under long-term storage conditions, the physical (i.e., T_g, HDT), mechanical (i.e., tensile strength, modulus, adhesive/cohesive strength), and chemical (as a result of oxidation, hydrolysis, etc.) properties of some of the components of the optical fiber bobbin system (i.e., core, cladding, primary buffer, secondary buffer, adhesive, splice areas, etc.) will change as a result of the effects from thermal cycling and

CTE mismatch, various humidity conditions, vibration during transport, and other inconceivable conditions.

Therefore, the properties of the total optical fiber bobbin system, as well as the individual system components, should be tested at

1. the lowest anticipated temperature after thermal/humidity/vibration cycling,

2. at room temperature after thermal/humidity/vibration cycling, and

3. at the highest anticipated temperature and humidity after thermal/humidity/vibration cycling.

Note: Considering items 1, 2, and 3 in terms of severity, high temperature, and humidity are the most detrimental factors in the aging of adhesive systems.[21]

By using environmental simulation equipment currently available in the marketplace and mimicking as closely as possible to the actual field storage conditions, one should be able to determine how some of these properties may change during long-term storage. However, it is probably unrealistic to extrapolate from short-term studies what the long-term effects and their magnitudes may be during long-term storage of the optical fiber bobbin system.

Some of the properties that might be informative would be how the adhesive and/or cohesive strength as well as the peel strength of the buffer and adhesive materials change over time as function of temperature/humidity/vibration, etc. One possible method that could be used to test the effects of these property changes while under various environmental conditions, would be to monitor the level of tension that is required to peel the fiber away from the bobbin.

Any adhesive studies that are undertaken should include an investigation (i.e., SEM, ESCA, etc.) to determine what type of failure occurred (adhesive or cohesive?) and where it occurred (near or at what interface?). Under hot, wet conditions it is conceivable that the failure could occur at the primary buffer/cladding interface leaving a bare glass surface. If this is indeed where the failure occurs, then owing to the brittleness of the core and cladding material, it is also conceivable that premature fiber fracture and/or significant microbending loss would result.

The moisture diffusion coefficient or the water vapor transmission rate should be determined. An alternative to determining the diffusion coefficient would be to perform a simple wicking test that involves using dyed water and the optical fiber or the specific UV-cured film and monitoring how fast the water diffuses as function of temperature and time. In addition, one should determine how the properties change after equilibrium moisture conditions have been reached.

Relevant ASTM test standards:

1. D 794 Determining permanent effect of heat on plastics.
2. D 3045 Heat aging of plastics without load.
3. D 756 Weight and shape changes of plastics under accelerated conditions.
4. D 3418 Transition temperatures of polymers by thermal analysis.
5. E 96 Water vapor transmission of materials.
6. D 570 Water absorption of plastics.
7. D 746 Brittleness Temperature of plastics and elastomers by impact.
8. D 1043 Stiffness properties of plastics as a function of temperature by means of a torsion test.

Given the fact that there is a very large number of UV-curable formulations available in the marketplace that have widely different properties and even more that could be custom formulated, it is imperative to optimize the coating, curing, and adhesion parameters for each selected formulation including

1. Determine the best UV exposure time and cure speed.

2. Determine the degree and uniformity of cure of the coating/adhesive as a function of thickness.

3. Match the UV lamp spectrum to the photoinitiator absorption spectrum.

4. Optimize the coating process, including the viscosity and rheology (i.e., Newtonian, shear thinning, shear thickening) of the coating/adhesive.

5. Determine the optimum thickness of the adhesive that is needed to achieve the required adhesive and cohesive strength.

6. Others.

FIBER DESIGN

New fiber design should be seriously considered. The DoD should not allow fiber manufacturers to set specifications for the fiber. New companies or new branches of existing companies would love an opportunity to respond to specialized development. One possibility would be a reinforced system with stranded spirals of carbon filament around a first thin buffer, followed by a second buffer layer. A configuration of that type could easily weight 30 to 50% less per unit length and be two to ten times stronger. It would also eliminate most of the concern for the strength of splicing joints and weakened sections of long optical fiber draws.

DEVELOPMENT OF STANDARDIZED TEST PROCEDURES

To ensure FOG-M system long-time reliability, we believe it will be necessary to develop a standard set of test procedures specifically designed for FOG-M components. A secondary recommendation is to contract an unbiased laboratory to conduct and document the formulated standardized tests.

The fiber optic test procedures in use today are primarily designed for telecommunication applications and were not designed with FOG-M applications in mind. Consequently, a need for *specific* standard test procedures exists for tethered fiber optic weaponry components. Included in these test procedures should be tests for each specific component with emphasis on the following parameters, where applicable: (1) temperature cycling, (2) aging, (3) minimum bend radius, (4) radiation hardening, (5) strength measurements, (6) humidity effects, (7) buffer integrity, (8) shock, (9) vibration, (10) attenuation, (11) insertion loss, (12) excess loss, and (13) directionality. Although fiber optic test procedures are well documented for many of the above parameters, we reiterate the necessity for specific test procedures to ensure all vendors are adhering to strict quality control standards.

DAY-NIGHT GUIDANCE SYSTEM

A new front-end missile optical configuration could probably be put into the existing mechanical assemblies. Using dichroic optics and wide band width lenses (both obtainable and adaptable) a combination infrared-visible observation system can be employed. The video readouts can be sent down the fiber with an additional multiplex step and the guidance officer will have both visible and infrared views for control. The huge advantage offered is both day and night control for the same system and better potential target identification during flight. Both factors could easily make the difference between a marginally useful and highly useful system. If desired, our experience at ORNL and our associations with other DOE and university groups for potential collaboration, make us especially qualified for the study and development of such a system.

TESTING NEEDS

We have laid out some proposed test programs to attempt to give an idea of the magnitude of each of the several issues. This should not be construed as a proposal with accurate cost estimates. ORNL is of course interested in contributing to the FOG-M program and would welcome the opportunity to submit estimates for proposed work.

Some of the tests we recommend are doubtlessly already being performed as a part of the current program. Others perhaps are not. Again, we imply nothing about the quality of the current technical plans or projects. In many, if not most, cases we simply have no information about what is actually being done. We submit this list in an effort to point out possible areas of new or intensified emphasis which will be helpful for the overall program goals.

ELECTRONIC COMPONENT AND OPTICAL FIBER PERFORMANCE TESTS IN CALIBRATED GAMMA RAY AND X-RAY ENVIRONMENTS, AND IN NUCLEAR REACTOR BEAM TUBES

EG&G-Las Vegas has a well calibrated ^{60}Co source for use in detector development. It or some other similar facility could be used for the photon tests. Several universities, such as Texas A&M and the University of Virginia, have excellent reactor facilities and would be good choices for the neutron tests. There are also good febetron (pulsed X-ray source) and related pulsed sources, both neutron and photon, at the major national laboratories such as Los Alamos and ORNL. EG&G has an excellent linear accelerator facility in Santa Barbara that can produce very short duration X-ray and electron bursts.

Costs

1. Preparation of test component samples and pretest reference calibrations: $35K
2. Field test at EG&G or similar facility, including setup, data collection and preliminary analysis: $55K
3. Travel: $8K
4. Materials (those required to be purchased): $10K
5. Documentation: $8K

Total: $116K Contingency: $15K

FIBER PAYOUT FIELD TESTS

For the increased range version of the missile system it is no longer a simple assumption that the optical fiber length will not be subjected to possibly-disruptive encounters during the flight of the missile. Longer flight paths and probably more rugged terrain will inevitably bring optical fiber strands into such encounters. Furthermore, explosives nearby, producing particulates at high velocities will have greater opportunity to cause damage if a longer cross section is available. Finally, the requirement of spliced fibers to produce the needed lengths will present the additional concern of weakened areas in the extension of fiber.

Observation of the full strand length, through fluorescence or some other specialized identification scheme, would be very useful. Such observation, using modern video and tracking techniques, could also help develop a collateral monitoring technology for these missiles; namely, a vehicle-borne observation system to observe flight to the exit horizon. Collateral monitoring can be especially useful in real battle conditions where numerous interruptions in visibility are not only possible but likely. Such monitoring could often get a missile through a smoke or dust cloud by orienting its entry and flight trajectory before an extended period of blackout.

Costs (Exclusive of MICOM Field Support)

Phase I. Selection and Calibration of Test Instrumentation

A. Evaluate test conditions, ranges of sensitivity, types of measurements required, expected and needed uncertainties, etc.: $30K

B. Modify and calibrate measurement systems for tests: $40 - $200K

C. Field test or tests: $50 - $500K

FULL-SCALE EFFECTS TEST AT NTS

At some time during the development program for the modern fiber optic guided missile, it is important, probably vital, to perform a nuclear effects test at the Nevada Test Site (NTS) to directly observe the effects of prompt radiation from a detonation. The electronics, the fiber optics, the engine, payload, optical systems, etc. can be operated or in use during the actual event. The missile surfaces and internals can be instrumented for temperature, shock, vibration, etc. In short, such a test effectively duplicates field conditions for a battle scenario with tactical nuclear weapons. Such a test should be a requirement, if it can be performed in current political climate, for any missile system designed for use in tactical nuclear conditions.

Approximate Costs (Exclusive of NTS support and test articles)

A. Preparations and calibrations: $40 - $100K

B. Field setup and calibrations, including cabling, etc.: $200 - $350K

C. Test and data analysis: $150 - $500K

Estimate $0.5 - $1.0M for total operation

FIBER PAYOUT TESTS AT HOT AND COLD TEMPERATURE EXTREMES

Cost Estimate: $30-60K plus materials

IDENTIFICATION OF PAYOUT PACKAGE FAILURE MODES

Through the use of potential problem analysis techniques, the most likely, critical modes should be identified. The effects of temperature, temperature cycling, moisture, vibration and shock, and adhesive bonding levels should be included. Test programs to gather basic data can be defined for those critical areas where information is lacking or inadequate.

IN-PROCESS DAMAGE

These activities would concentrate on defining the degree and type of damage caused by passive mechanisms such as aging in storage and on active mechanisms such as damage caused by the type, size and speed of contact points encountered during bobbin winding.

QUALIFICATION/QUALITY ASSURANCE PROGRAMS

This would be an effort to plan the degree and methods for qualifying the fiber drawing and bobbin winding processes. In addition to the initial qualification process, the need for in-process controls would be established as would the testing methods necessary on the final product (fiber and bobbin). These test methods would form the basis for acceptance and must be related to the payout application.

SPLICES

Basic development of methods and equipment to produce splices which will perform in the payout environment is needed.

STANDARDIZED TEST PROCEDURES DEVELOPMENT

Phase 1. Facility Preparation $45K and 3 months

In the first task, our facilities will be modified to accommodate the FOG-M quality control testing requirements. This will include ORNL safety approval document preparation for radiation hardening tests, laser operation, etc., the designation and modification of laboratory space, equipment transporting costs, and manpower.

Phase 2. Formulation of Quality Assurance Procedures $73K and 6 months

This task entails the formulation of specific test procedures for each of the components listed in subsequent phases. This will include where applicable: (1) temperature cycling, (2) aging, (3) minimum bend radius measurements, (4) break-point bend radius measurements, (5) strength measurements, (6) humidity effects, (7) buffer integrity, (8) shock, (9) vibration, (10) attenuation, (11) excess loss, (12), insertion loss, (13) directionality, and (14) radiation hardening.

Phase 3. Coupler Quality Assurance $62K and 15 months

After reviewing the FOTPs and formulating a specific set of test procedures, the various couplers supplied by Gould, Amphenol, Canstar, Aster, and others will be tested to insure long term survivability. A report detailing the results will be written for purposes of vendor selection and FOG-M system analysis. Specific items to be included are

(1) temperature cycling; (2) aging; (3) humidity effects; (4) strength measurements; (5) shock; (6) vibration; (7) excess loss; (8) insertion loss; (9) directionality, and, if applicable, (10) radiation hardening. Also, the dependence of each of these parameters on each other will be investigated and statistical results generated.

Phase 4. Fusion Splice/Connector Quality Assurance $57K and 15 months

Similar to the above task, the fusion splices and connectors required in the FOG-M system will be tested to insure long term survivability. Specific items included will be (1) temperature cycling, (2) aging, (3) minimum bend radius measurements, (4) break point bend radius measurements, (5) strength measurements, (6) humidity effects, (7) buffer integrity, (8) shock, (9) vibration, (10) loss, (11) directionality, and (12) radiation hardening. The effort will result in a final report similar to those described above.

Phase 5. Optical Fiber Quality Assurance $60K and 15 months

Several spools of optical fiber supplied by the vendors discussed throughout this document will be subjected to tests to ensure long-term survivability. Specific items included will be (1) temperature cycling, (2) aging, (3) minimum bend radius measurements, (4) break point bend radius measurements, (5) strength measurements, (6) humidity effects, (7) buffer integrity, (8) shock, (9) vibration, (10) loss, (11) directionality, (12) attenuation, and (13) radiation hardening. The effort will result in a final report similar to those described earlier.

CONCLUSIONS

The ORNL team has presented in this report several ideas that we believe to be of importance to the FOG-M program's success. We would suggest that MICOM consider these ideas and that subsequent dialogue might lead to continued involvement by the ORNL team as well as other branches of ORNL in an expanded role. We would point out that ORNL could contribute in many areas not necessarily mentioned in this report, such as image sensor development.

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Appendix A

SPECTRAGUIDE™ RADIATION HARD OPTICAL FIBER PRODUCT INFORMATION

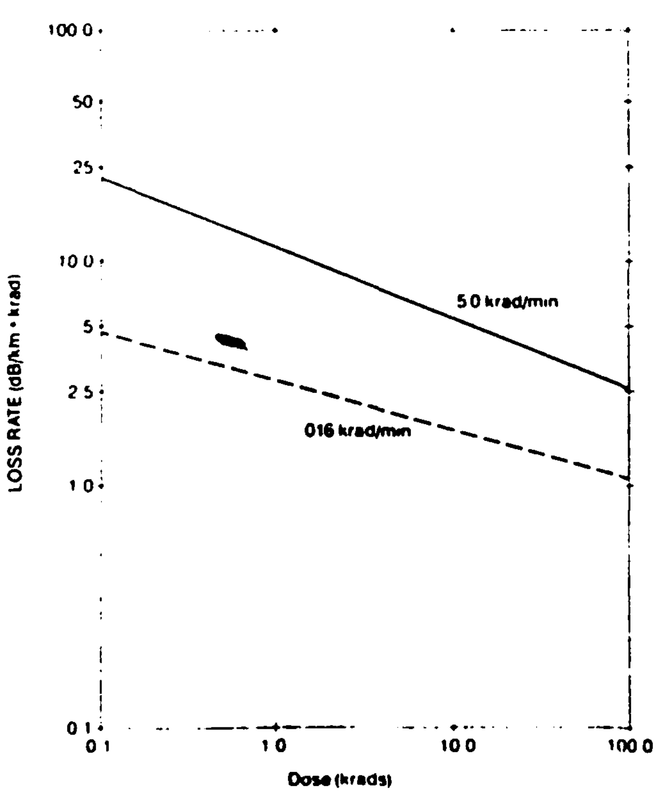
SpecTraguide™
Radiation Hard Optical Fiber

Quality and durability
All SpecTran optical fibers are easily spliced by both fusion and mechanical techniques. A unique dual epoxy acrylate coating cushions the fiber core, ensuring long fiber life and limiting microbend loss.

Radiation Hard fiber construction
SpecTran multimode and single-mode fiber compositions optimize radiation resistance over a wide range of dose rates, dose levels and temperatures.

Superior resistance to induced loss
As shown below, SpecTran 400-Series multimode products effectively limit induced loss over a wide range of dose rates and total dosages.

Loss Rate vs Gamma Radiation Dose
420R 850 nm 23° C



Contact our Applications Engineering Department for technical assistance regarding radiation-induced losses in optical fiber. Our extensive experience is available to you at any stage of project design or development.

100% quality tested
We test every spool of SpecTraguide fiber for quality and performance. As a member of the Electronic Industries Association, we use standard industry test procedures to characterize our fiber for more than 25 individual performance parameters. Spool labels detail exact performance data.

Our commitment
We deliver on time, as promised and we back our products with responsive service and technical support. For both standard and special-use fiber, a growing list of customers depends on the SpecTran commitment

Special applications
SpecTran is one of the world's leading designers and manufacturers of optical fiber. In addition to Radiation Hard fiber, we offer: Single-mode, Step Index Multimode (single/dual window), Graded Index Multimode (single/dual window), Hermetically Coated, UV Transmitting, Infrared Transmitting and PYROCOAT™ Heat Resistant fiber. We can also develop special-use fiber to meet unique and demanding applications. Contact our Applications Engineering Department for further information.

To order:
Refer to the Product Specifications Chart to determine the product(s) best suited to your application. Order that product number, followed by the letter R to specify Radiation Hard fiber.
Specify the attenuation (first, FW; second, SW; or dual, DW), bandwidth and length required.
Please contact the Sales Department
617 765 0851
FAX 617 347 2747
for minimum order requirements and further details.

SpecTran Corporation
50 Hall Road
Sturbridge, MA 01566
617 347 2261
Telex 709816

SpecTran reserves the right to improve, enhance and modify the features and specifications of SpecTran products without prior notification

SpecTran™

SpecTraguide™
Radiation Hard Optical Fiber

Radiation can penetrate the core of optical fiber, causing an increase in attenuation which may interrupt communications. SpecTraguide Radiation Hard optical fiber is specially designed to resist radiation, ensuring accurate, uninterrupted communications in the vicinity of a controlled radiation source or nuclear event.

SpecTraguide Radiation Hard fiber is the product of an exhaustive research and testing program. In evaluations conducted by U.S. government agencies, including the Naval Research Laboratory and the Harry Diamond National Laboratory, SpecTraguide's loss resistance and recovery rates were proven exceptional.

- ☐ Available in both single-mode and multimode constructions
- ☐ Qualified for advanced defense applications including AEGIS, FEMA and the Ground Launch Cruise Missile program
- ☐ Recommended for use in and around all radiation sources

		Graded Index			Step Index		Single-mode
Product Number		200R	320R	420R	820R[1]	840R[1]	102[3]
Core Diameter	um	50	100	100	105	200	—
Clad Diameter	um	125	140	140	125	240	125
Buffer Diameter	um	500	500	500	500	500	250
Numerical Aperture	um	.20	.27	.24[2]	.20[2]	.20[2]	—
Mode Diameter 1300 nm	um						10.0
Attenuation (Max) @850 nm	dB/km	4.0	5.0	5.0	15.0	15.0	—
@1300 nm	dB/km						.50
@1550 nm	dB/km						.35
Bandwidth (Min) @850 nm	MHz-km	200	100	20	20	20	
Length	km	----- 1.1-2.2 -----					2.2-12.6
Strength (Min)	kpsi	100	100	100	50	50	50

[1] Pure silica core [2] Measured using long NA technique [3] Standard single-mode products

Appendix B

AT&T RADIATION HARDENED FIBER PRODUCT INFORMATION

AT&T Radiation Hardened Fiber

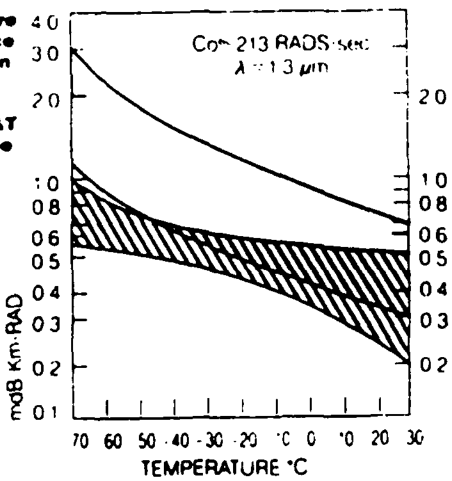
Uses/Applications

Fiber optic systems that must operate in nuclear radiation environments. Applications include tactical military, undersea, avionics and shipboard.

Features

- Available with single mode or multimode fibers
- 100 kpsi proof test standard
- Microbend resistant fiber designs
- Qualified to military spec for radiation (CR-CS-0051-001)
- Compatible with a complete line of cable and connector products including tactical military cable products
- Excellent geometric characteristics for good splicing results
- Excellent radiation resistance over wide temperature range

Temperature Dependence of Radiation Induced Losses in Typical AT&T Single Mode Fibers



Description

AT&T Radiation Hardened fiber exhibits superior resistance to nuclear radiation, both with respect to added loss and recovery rate, over a wide operating temperature range. This performance has been demonstrated for low and high level radiation environments. The phosphorous levels in the fiber designs are balanced to optimize performance at both low and room temperatures. The 50/125 micron multimode fiber and the depressed cladding single mode fibers have been qualified for operation under the environmental conditions described in CR-CS-0051-001, Fiber Optic Transmission System Long Haul Development Specification, distribution limited to DOD agencies and contractors with a need to know.

A dual protective coating is applied over the fiber cladding to cushion the fiber against microbending losses, provide abrasion resistance, and preserve the mechanical strength of the glass. Each fiber is proof tested so that it will survive the installation loads and the associated long-term residual stresses, even under extreme environmental conditions. Finally, each fiber is measured for optical and dimensional properties for compliance to all specifications listed in the respective data sheets.

Specifications:

Multimode

Clad Diameter: 125 ± 2 μm
Core Diameter: 50 ± 3 μm
Core Eccentricity: <6%
Core Ovality: <6%
Numerical Aperture: 0.23
Attenuation range:
2.8-4.0 dB/km at 850 nm
0.75-1.5 dB/km at 1300 nm
Bandwidth range:
150-400 MHz-km at 850 nm
150-600 MHz-km at 1300 nm
Coating dia: 250 ± 15 μm

Single Mode

Clad Diameter: 125 ± 2 μm
Core Diameter: 8.3 μm nominal
Core Eccentricity: ≤ 1 μm
Attenuation range:
0.35-0.5 dB/km at 1310 nm
0.20-0.3 dB/km at 1550 nm
Zero dispersion wavelength
1310 ± 10 nm
Dispersion (1285-1330 nm)
3.2 ps/nm-km max
Refractive Index Delta: 0.37%
Coating dia: 250 ± 15 μm
Mode field dia: 8.8 ± 0.7 μm
Cutoff wavelength: 1350 nm max
(2 m reference length)

For more information, please contact your AT&T Representative.

AT&T Technologies, Inc. reserves the right to make changes to the product(s) described in this document in the interest of improving internal design, operational function, and/or reliability. AT&T Technologies, Inc. does not assume any liability which may occur due to the use or application of the product(s) described herein.

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Appendix C

CORGUIDE® OPTICAL FIBER PRODUCT INFORMATION

CORNING
Telecommunications Products Division
Corning Glass Works
Corning, New York 14831, USA
Tel 607-974-4411
Telex 932498

Corguide® Optical Fiber

Product Information

Payout™ Single-Mode Fiber

Issued 2/89

1.0 Introduction

Corning has developed a specialized fiber for use in specialty applications that require additional resistance to bend-induced attenuation. Such applications include tethered weapons, remotely piloted vehicles with optical-fiber tethers, microcables, and optical sensors. Payout™ fiber is coated with CPC5 coating, an abrasion-resistant acrylate.

Corning Payout™ fiber is designed to operate at 1300 nm and 1550 nm. The fiber exhibits excellent microbending and macrobending performance characteristics. Corning can design and produce Payout™ fiber with a variety of cladding and coating diameters.

2.0 *Product Parameters**

Cutoff Wavelength		≤1300 nm
Attenuation	@ 1300 nm	≤0.7 dB/km
	@ 1550 nm	≤0.4 dB/km
Mode-Field Diameter	@ 1300 nm	5.5 µm
	@ 1550 nm	6.5 µm
Dispersion	@ 1300 nm	-20 ps/nm·km ≤ D ≤ 20 ps/nm·km
	@ 1550 nm	-20 ps/nm·km ≤ D ≤ 20 ps/nm·km
Cladding Outside Diameter		125 µm
Coating Outside Diameter		250 µm
Proof Test		Up to 400 kpsi
Standard Lengths		2.2 - 12.6 km

* A more comprehensive Product Information document will be issued by mid 1989.

For more information about Corning Payout™ single-mode fiber, contact Advanced Fiber Products, Corning Glass Works, MP-RO-03, Corning, N.Y. 14831, or call (607) 974-4144.

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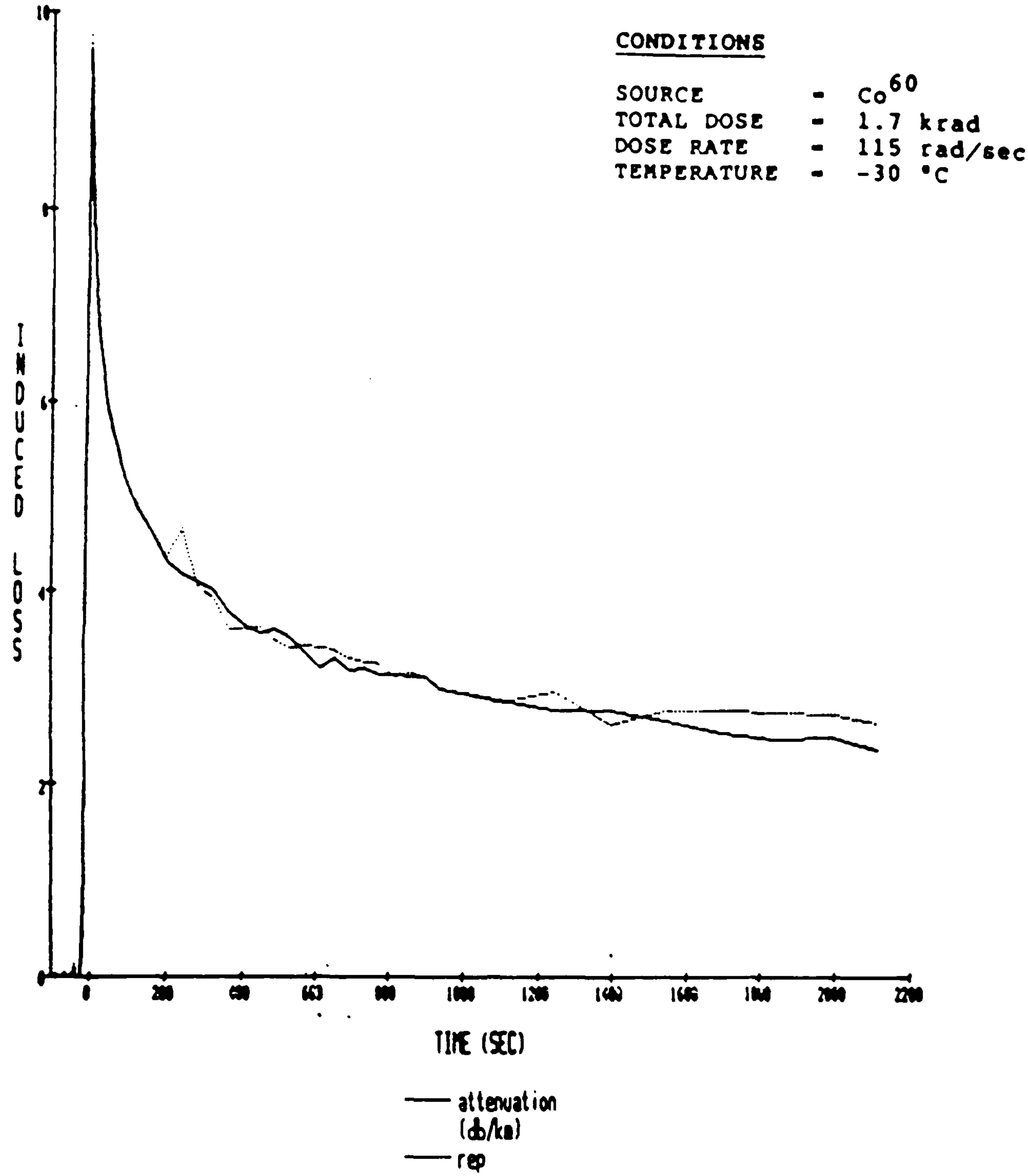
Developmental Optical Fiber Warranty

This warranty relates to optical fibers which are currently undergoing development and testing. Corning warrants that each reel of these fibers sold by it meets applicable specifications for mechanical strength, light attenuation, and bandwidth. Corning makes no warranty, however, as to the results to be obtained from the use of these fibers. Moreover, Corning reserves the right to change these fibers and/or their manufacturing or measurement techniques in the future. If any of these fibers fail to satisfy this warranty, Corning's sole obligation will be to provide replacement fibers. In no event shall Corning be responsible for removal or installation costs or other incidental or consequential damages. THE FOREGOING WARRANTY IS IN LIEU OF ALL OTHER WARRANTIES EXPRESSED OR IMPLIED INCLUDING THE WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE.



RADIATION RESPONSE AT 1300 NM,
FIBER ID - 303196157405

*Provided by Corning Glass Works

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